Cosmological Neutrinos

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FRAMEWORK

What can the Universe Large Scale Structure (LSS)
tell us about cosmological neutrinos?

QUESTIONS TO BE ADDRESSED

1) Can they be probed by looking at their energy density contribution?

2) Can they be probed by looking at their perturbations?

3) Have we detected departures from the standard/expected Cosmic Neutrino Background (CNB)?

4) Are these findings robust?

5) Are there perspectives of discoveries in the next few years?

CNB in the relativistic regime

CNB predicted in 1953 by Alpher et al.

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*,†

RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
(Received September 10, 1953)

$$\omega_R = \omega_\gamma \left(1 + N_{eff} \times 7/8\, (4/11)^{4/3}\right) \quad \text{with } N_{eff} = 3.046$$

in the relativistic regime

Planck (CMB) + several other combinations yield evidence of $N_{eff} > 0$ at a level between 10-17σ

CNB in the non relativistic regime

➔ $$\omega_M = \omega_b + \omega_{CDM} + (\Sigma\, m_\nu) / 93.14\ \text{eV}$$

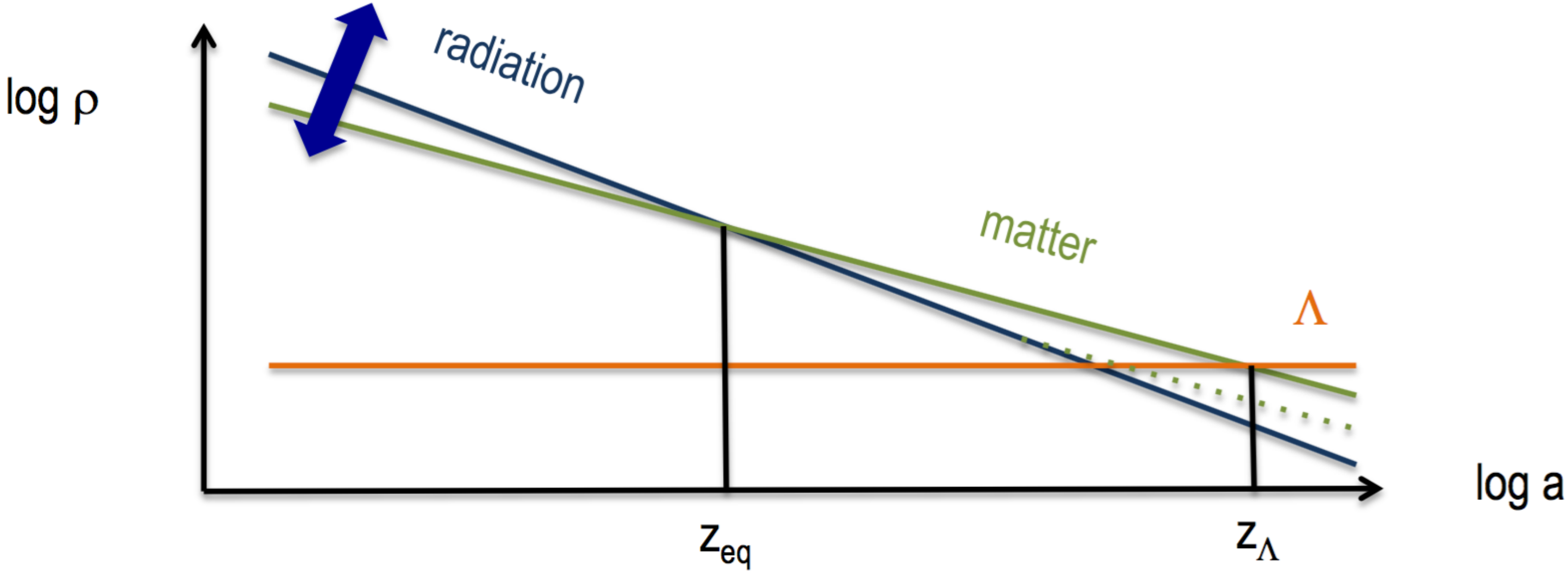
➔ Impact on the matter clustering through neutrino free streaming, impact on CMB statistics (angular diameter distance, Late ISW effect)

No convincing evidence for this effect, i.e. a non zero total mass

(although be aware that claims have been made)

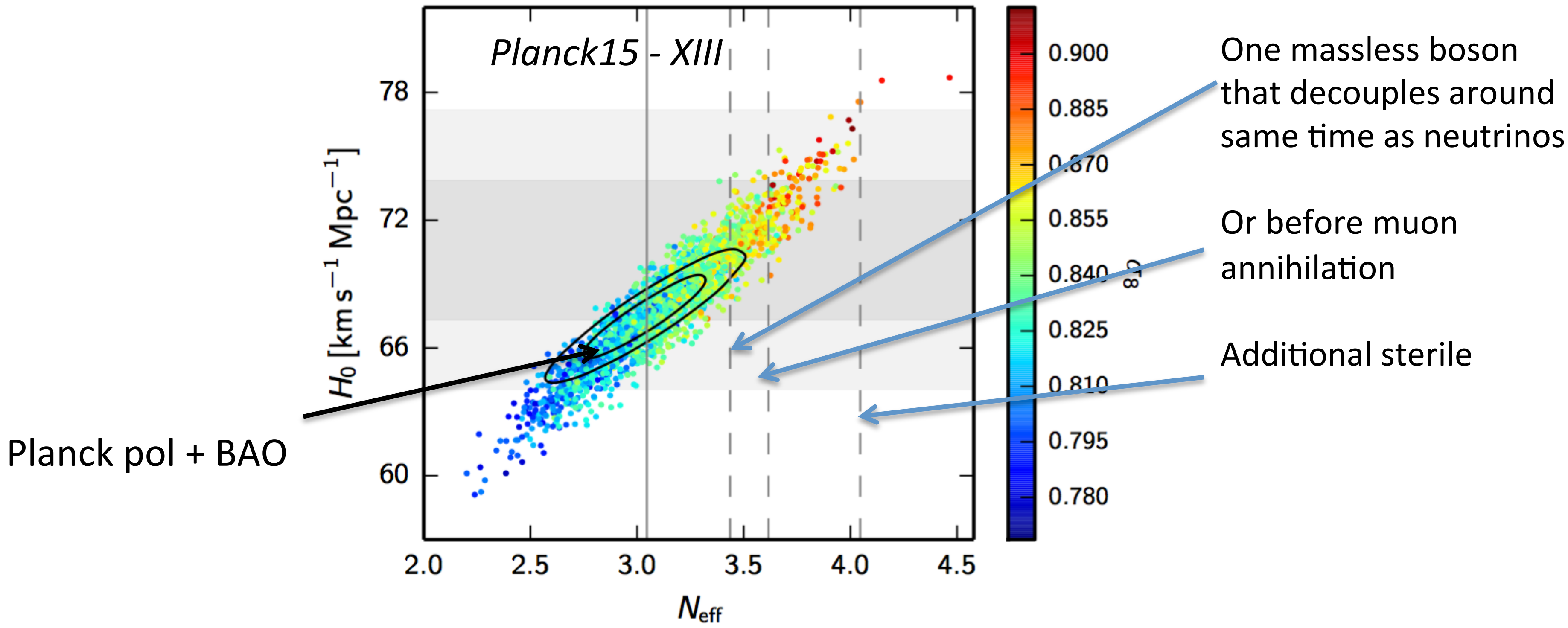
Measuring N_{eff} - CNB average density

Key issue: exploiting different evolution of the matter and radiation energy densities



There is an obvious degeneracy: can preserve all redshifts by increasing N_{eff}, H0 and keeping energy densities fixed – However this will cause more damping in the CMB power spectrum.

Measuring N_{eff} - CNB average density - II

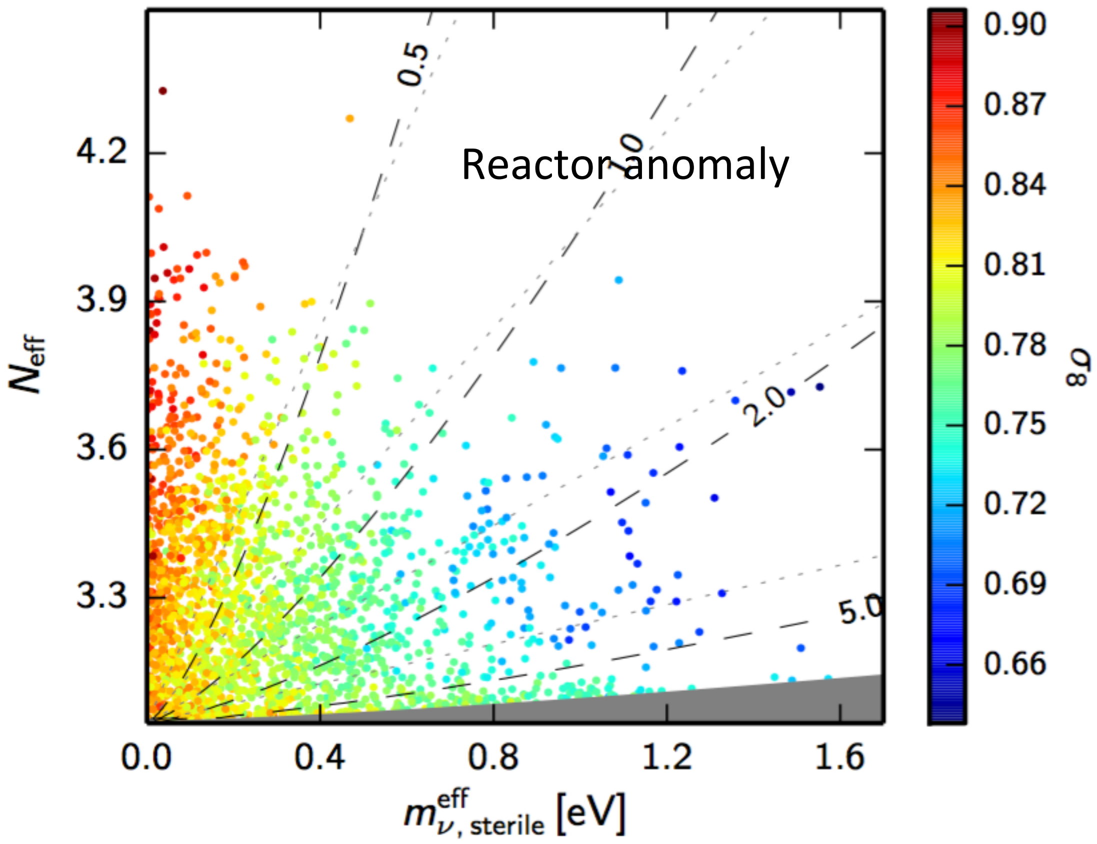


$$N_{eff} = 3.13 \pm 0.32 \quad \textit{Planck} \text{ TT+lowP};$$
$$N_{eff} = 3.15 \pm 0.23 \quad \textit{Planck} \text{ TT+lowP+BAO};$$
$$N_{eff} = 2.99 \pm 0.20 \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$
$$N_{eff} = 3.04 \pm 0.18 \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

In this relativistic regime, perturbations have been tested and support the view that this contribution to Neff is really made by neutrinos (and not by other particles).

Measuring N_{eff} - Extra relics? Most likely not

Planck15 - XIII



Search motivated by short baseline oscillation anomaly (LSND, MiniBoone, reactor data…)

General parameterization: (one massive sterile neutrino)

N_{eff} : parameter for relativstic density at early times

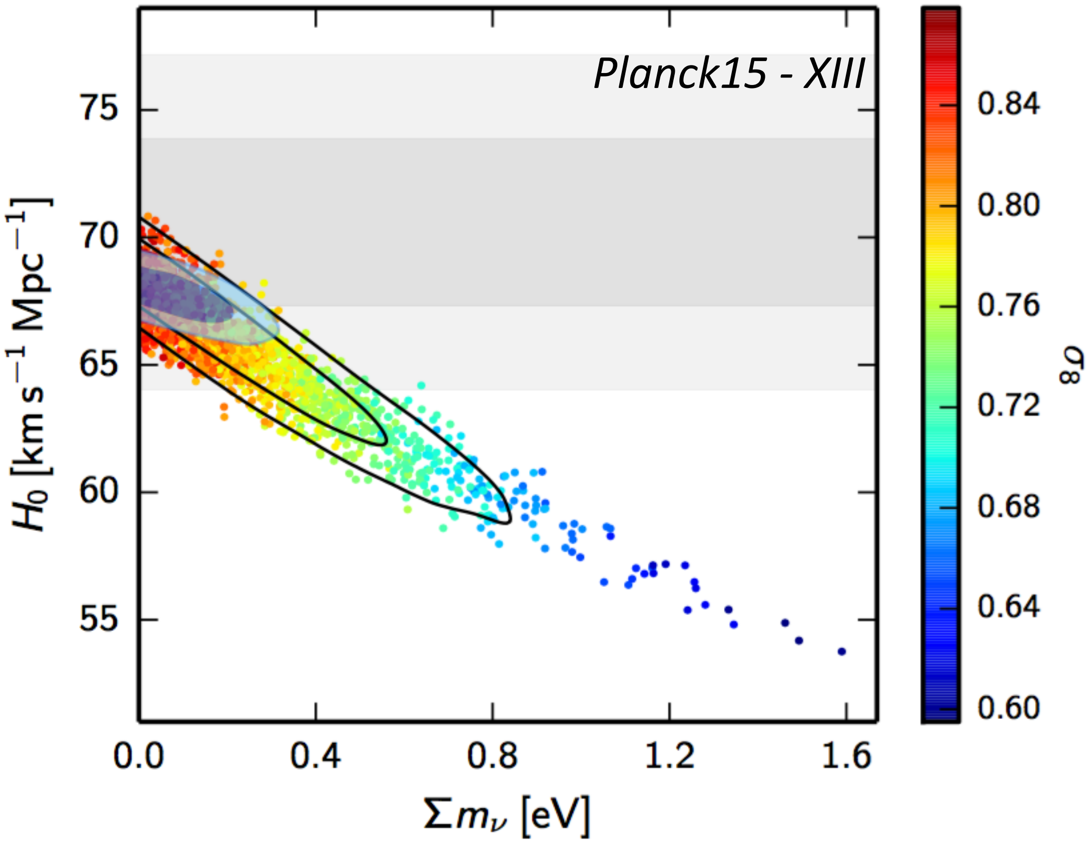
m_{eff} : parameter for non–relativistic mass of HDM today ($\omega_{HDM} = m_{eff} / 93.14$eV)

$$\left.\begin{array}{r} N_{eff} < 3.7 \\ m^{eff}_{\nu,\,sterile} < 0.38 \text{ eV} \end{array}\right\} \text{95\%, } \textit{Planck} \text{ TT+lowP+lensing+BAO.}$$

Models with Δ Neff=1 highly Disfavoured by Planck

Models with Δ Neff=0.4 mildly Disfavoured but require higher σ_8 and H_0

Total neutrino mass from the CMB



3 key parameters: power spectrum amplitude, neutrino masses and H0

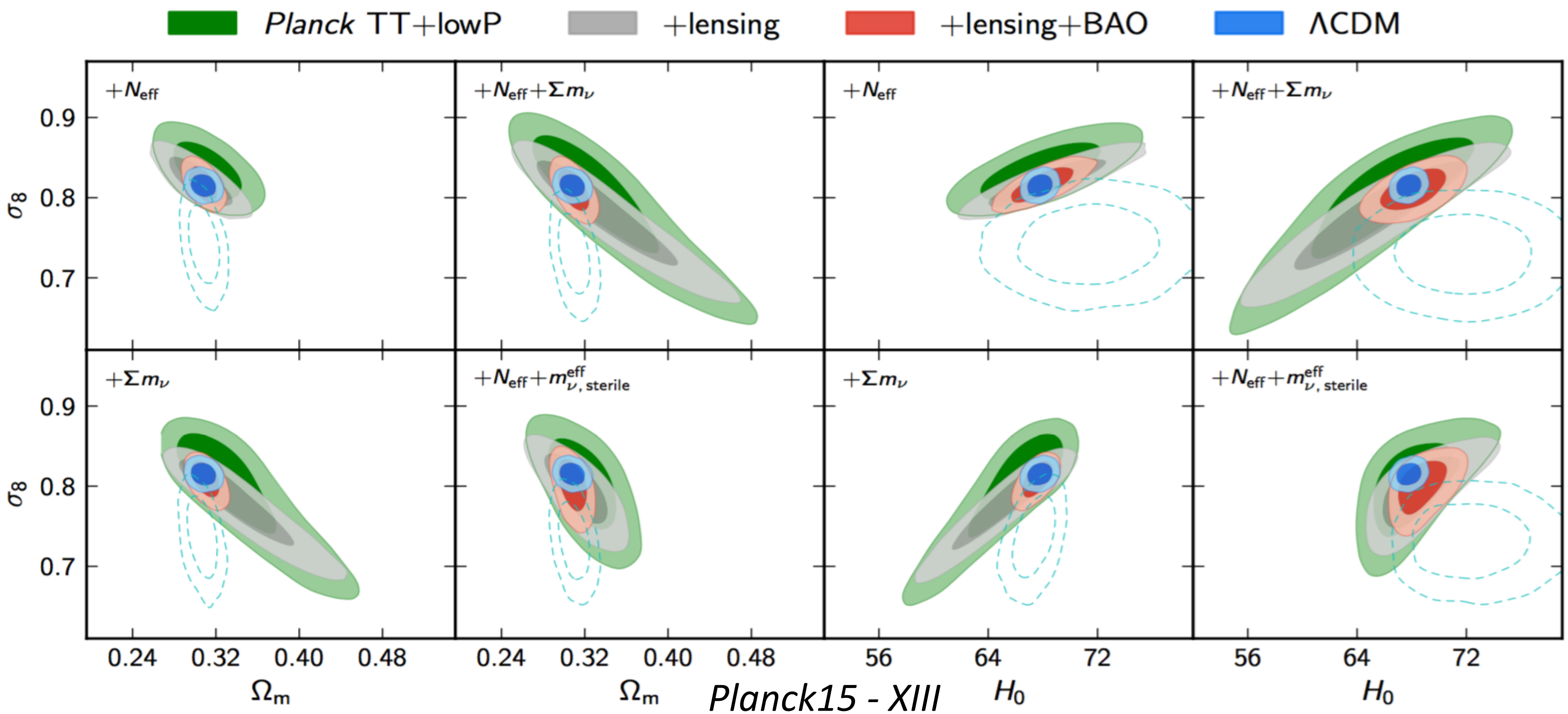
$\sum m_\nu < 0.72$ eV *Planck* TT+lowP ;

$\sum m_\nu < 0.21$ eV *Planck* TT+lowP+BAO ;

$\sum m_\nu < 0.49$ eV *Planck* TT, TE, EE+lowP ;

$\sum m_\nu < 0.17$ eV *Planck* TT, TE, EE+lowP+BAO .

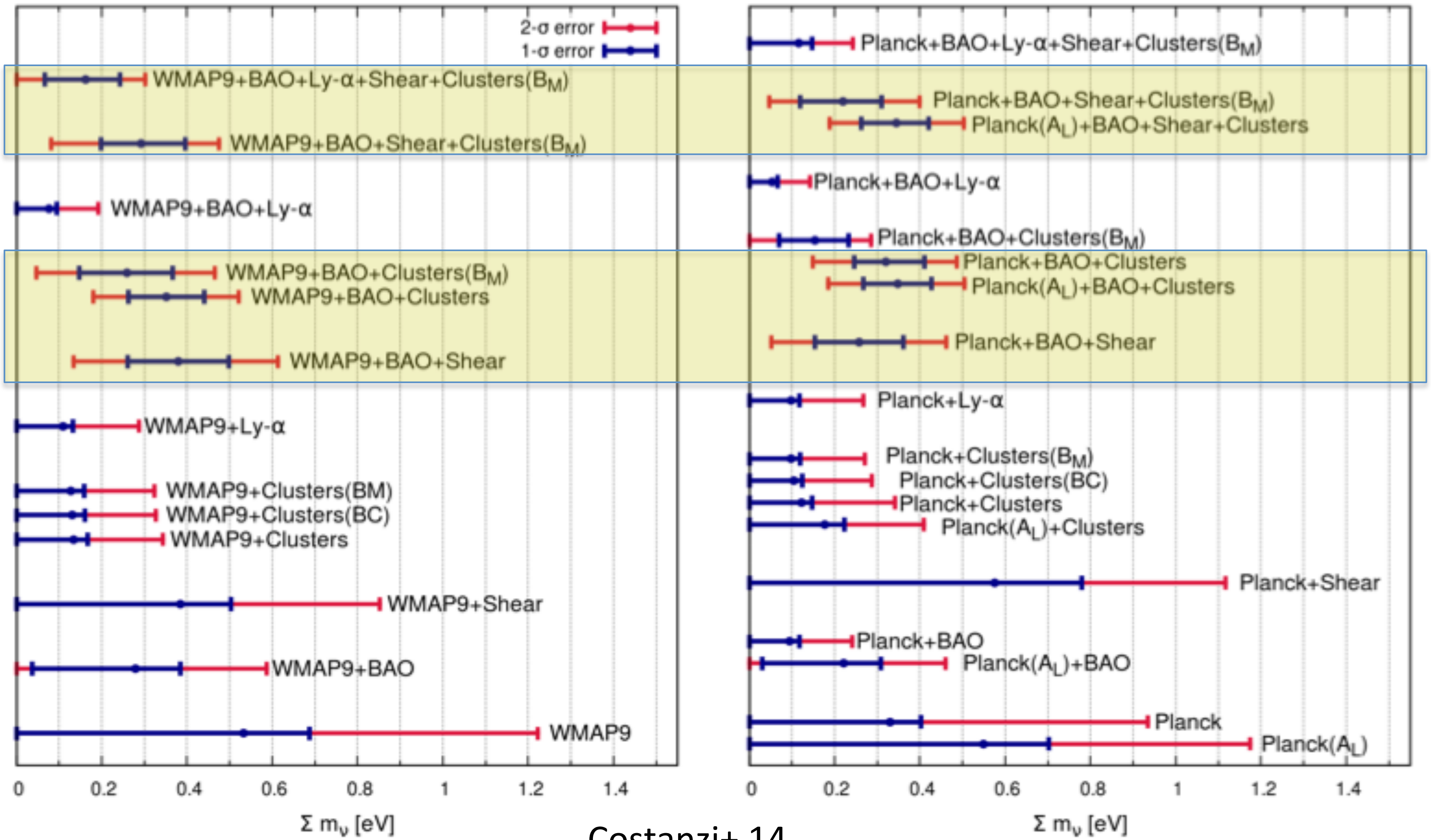
Departing from LCDM using neutrinos is difficult



Planck15 - XIII

Claims of non zero neutrino mass 0.3 ± 0.1 eV appear to be a compromise to reconcile low σ_8 values suggested by weak lensing and/or cluster number counts – some is true for the sterile sector.

Data combination after Planck 13…



Costanzi+ 14

Possible surprises/systematic effects?

Tension with CMB data H_0 value between 2 and 3σ

A 2.4% Determination of the Local Value of the Hubble Constant[1]

Adam G. Riess[2,3], Lucas M. Macri[4], Samantha L. Hoffmann[4], Dan Scolnic[2,5], Stefano Casertano[3], Alexei V. Filippenko[6], Brad E. Tucker[6,7], Mark J. Reid[8], David O. Jones[2], Jeffrey M. Silverman[9], Ryan Chornock[10], Peter Challis[8], Wenlong Yuan[4], and Ryan J. Foley[11,12]

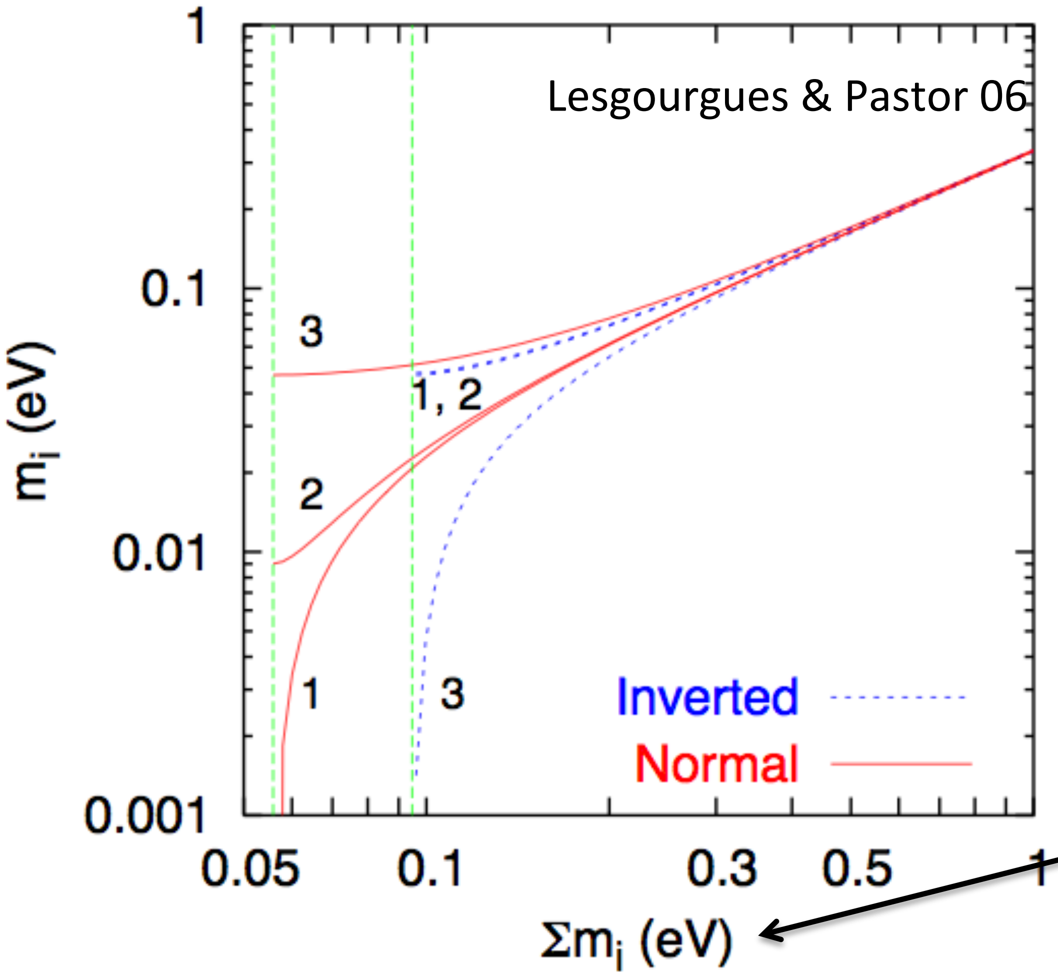
km s^{-1} Mpc^{-1}, respectively. Our best estimate of $H_0 = 73.02 \pm 1.79$ km s^{-1} Mpc^{-1} combines the anchors NGC 4258, MW, and LMC, and includes systematic errors for a final uncertainty of 2.4%. This value is 3.0σ higher than 67.3 ± 0.7 km s^{-1} Mpc^{-1} predicted by ΛCDM with 3 neutrino flavors having a mass of 0.06 eV and the *Planck* data, but the discrepancy reduces to 2.0σ relative to the prediction of 69.3 ± 0.7 km s^{-1} Mpc^{-1} based on the comparably precise combination of *WMAP*+ACT+SPT+BAO observations, suggesting that systematic uncertainties in cosmic microwave background radiation measurements may play a role in the tension.

If we take the conflict between *Planck* high-redshift measurements and our local determination of H_0 at face value, one plausible explanation could involve an additional source of dark radiation in the early Universe in the range of $\Delta N_{eff} \approx 0.4 - 1$. We

Impact on structure formation

i.e. neutrino perturbations

COSMOLOGICAL NEUTRINOS - I: STARTING POINT



COSMOLOGY

constraints on the sum of the neutrino masses

$$0.056\,(0.095)\ \text{eV} \lesssim \sum_i m_i \lesssim 6\ \text{eV}$$

COSMOLOGICAL NEUTRINOS - II: FREE-STREAMING SCALE

Neutrino thermal velocity

$$v_{\rm th} \equiv \frac{\langle p \rangle}{m} \simeq \frac{3T_\nu}{m} = \frac{3T_\nu^0}{m}\left(\frac{a_0}{a}\right) \simeq 150(1+z)\left(\frac{1\,{\rm eV}}{m}\right){\rm km\,s^{-1}}$$

Neutrino free-streaming scale

$$k_{FS}(t) = \left(\frac{4\pi G\bar{\rho}(t)a^2(t)}{v_{\rm th}^2(t)}\right)^{1/2}$$

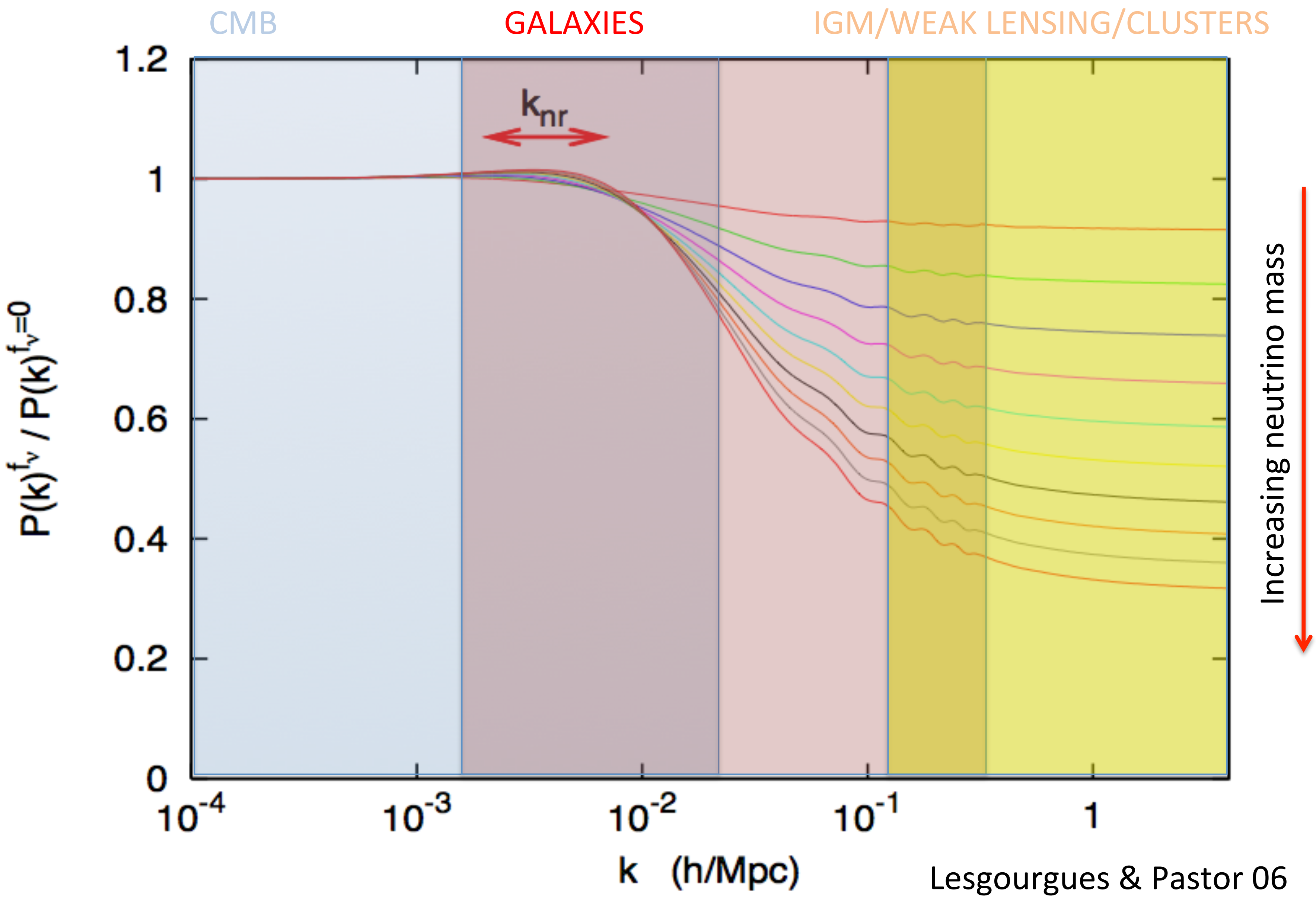
Scale of non-relativistic transition

$$k_{\rm nr} \simeq 0.018\ \Omega_{\rm m}^{1/2}\left(\frac{m}{1\,{\rm eV}}\right)^{1/2} h\,{\rm Mpc}^{-1}$$

THREE COSMIC EPOCHS	
	RADIATION ERA z>3400
	MATTER RADIATION z<3400
	NON-RELATIVISTIC TRANSITION z ~ 500

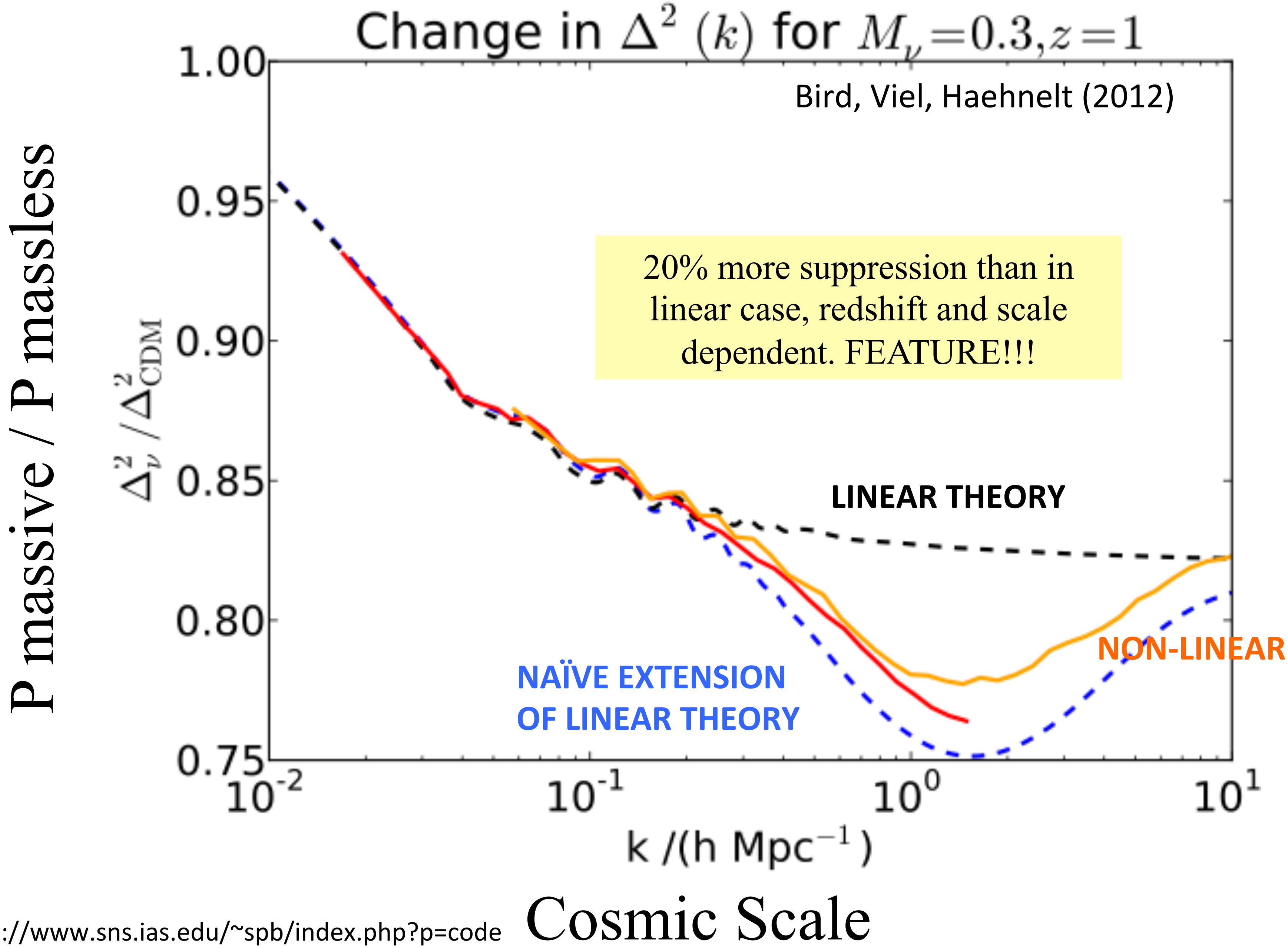
Below k_{nr} there is suppression in power at scales that are cosmologically important

COSMOLOGICAL NEUTRINOS - III: LINEAR MATTER POWER



Lesgourgues & Pastor 06

COSMOLOGICAL NEUTRINOS : NON-LINEAR MATTER POWER

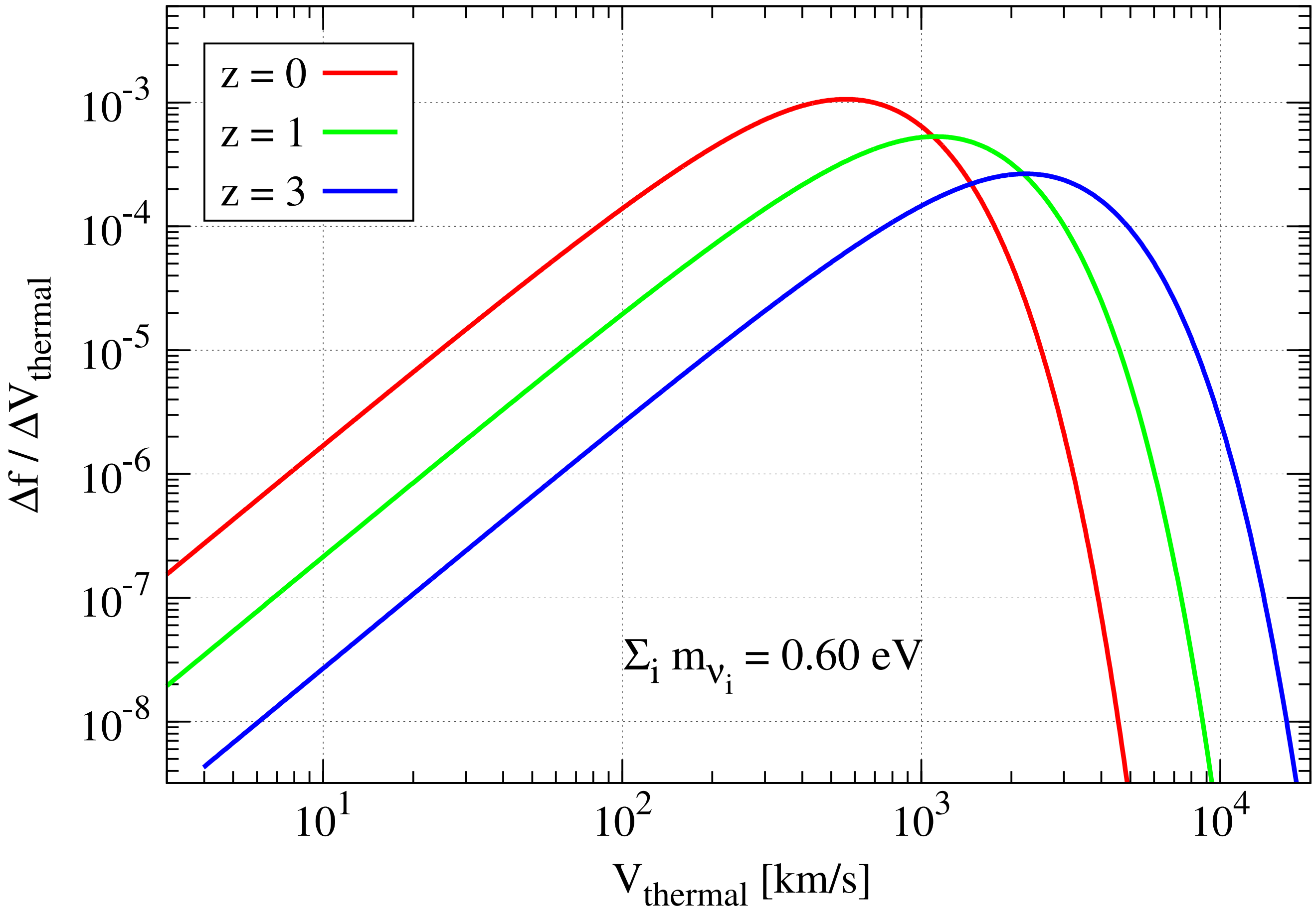


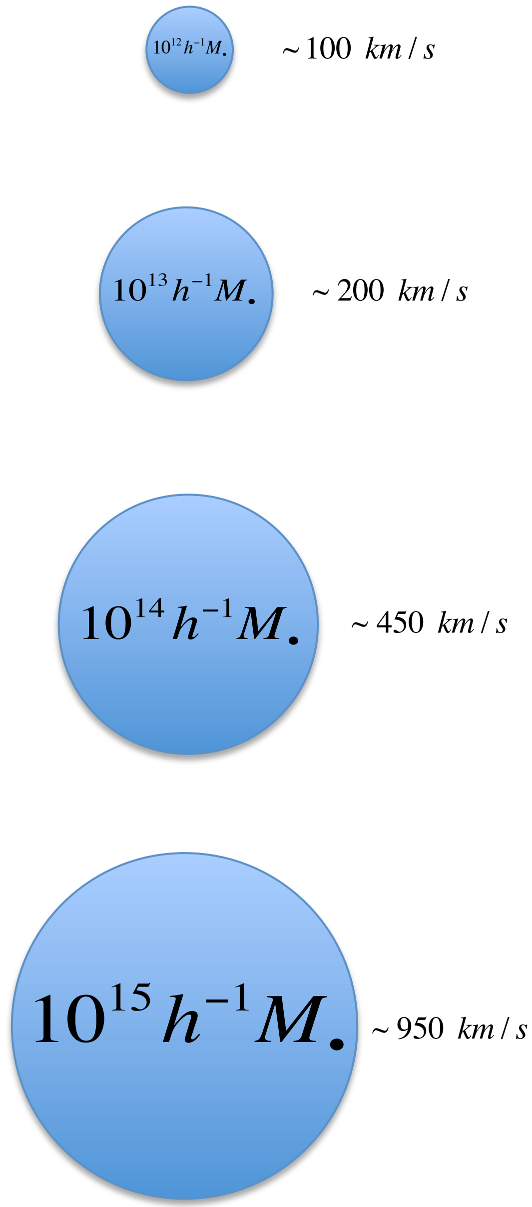
http://www.sns.ias.edu/~spb/index.php?p=code

Neutrino clustering

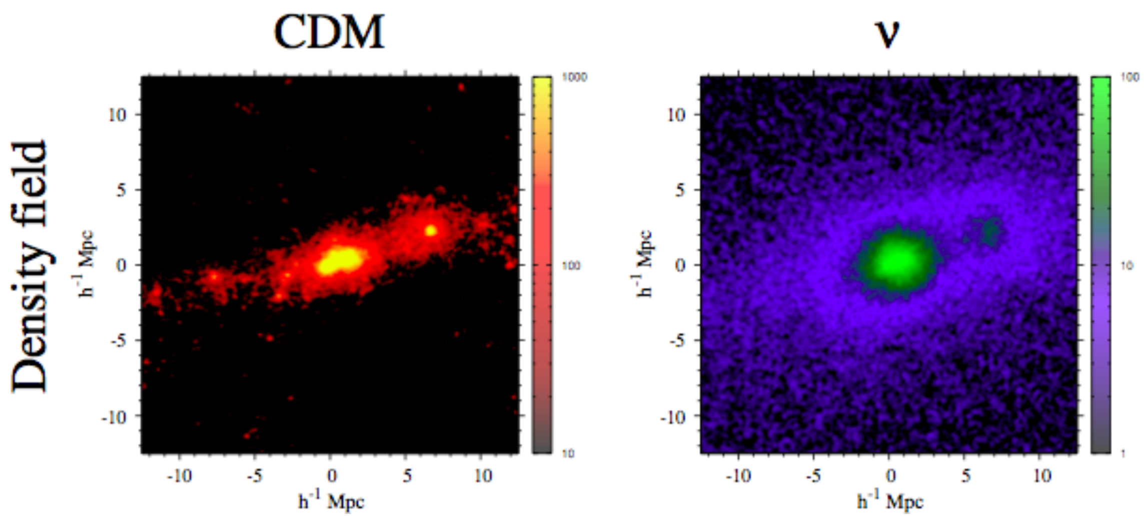
$$n_\nu(p,z)dp \cong \frac{4\pi g_\nu}{(2\pi\hbar c)^3}\left(\frac{p^2 dp}{e^{\left(p/k_B T_\nu(z)\right)}+1}\right)$$

$$T_\nu(z) = 1.95(1+z)\ K$$

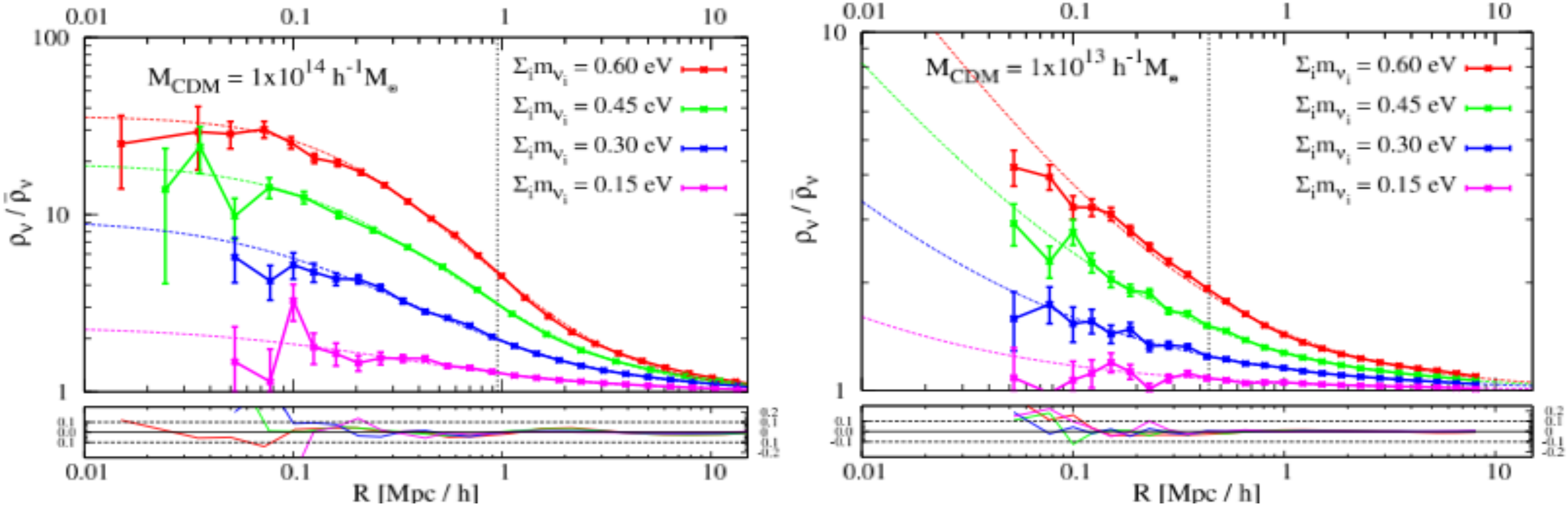




THE NEUTRINO HALO?



$$\delta_\nu(r) = \frac{\rho_\nu(r) - \bar{\rho}_\nu}{\bar{\rho}_\nu} = \frac{\rho_c}{1 + (r/r_c)^\alpha}$$



Villaescusa-Navarro, Bird, Garay, Viel, 2013, JCAP, 03, 019
Marulli, Carbone, Viel+ 2011, MNRAS, 418, 346

Halo mass function

Castorina, Sefussati, Sheth, FVN, Viel 2013

FoF halos : b=0.2

$$\frac{dn(M,z)}{dM} = \nu f(\nu)\frac{\rho_m}{M^2}\frac{d\ln\nu}{d\ln M}$$

Universal?

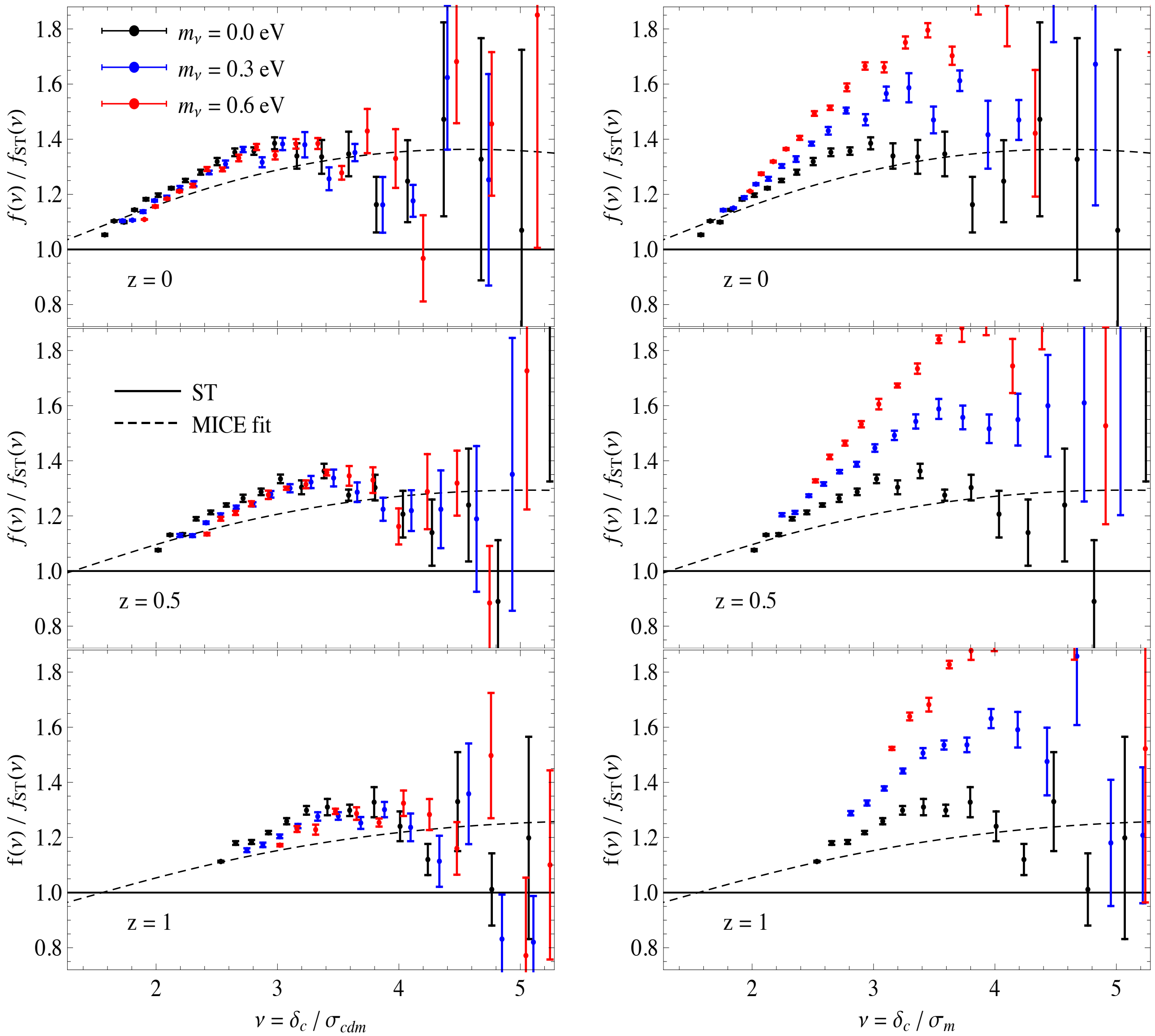
$$f(\nu) = \frac{M^2}{\rho}\frac{1}{\nu}\frac{d\ln M}{d\ln\nu}\frac{dn(M,z)}{dM}$$

Matter prescription

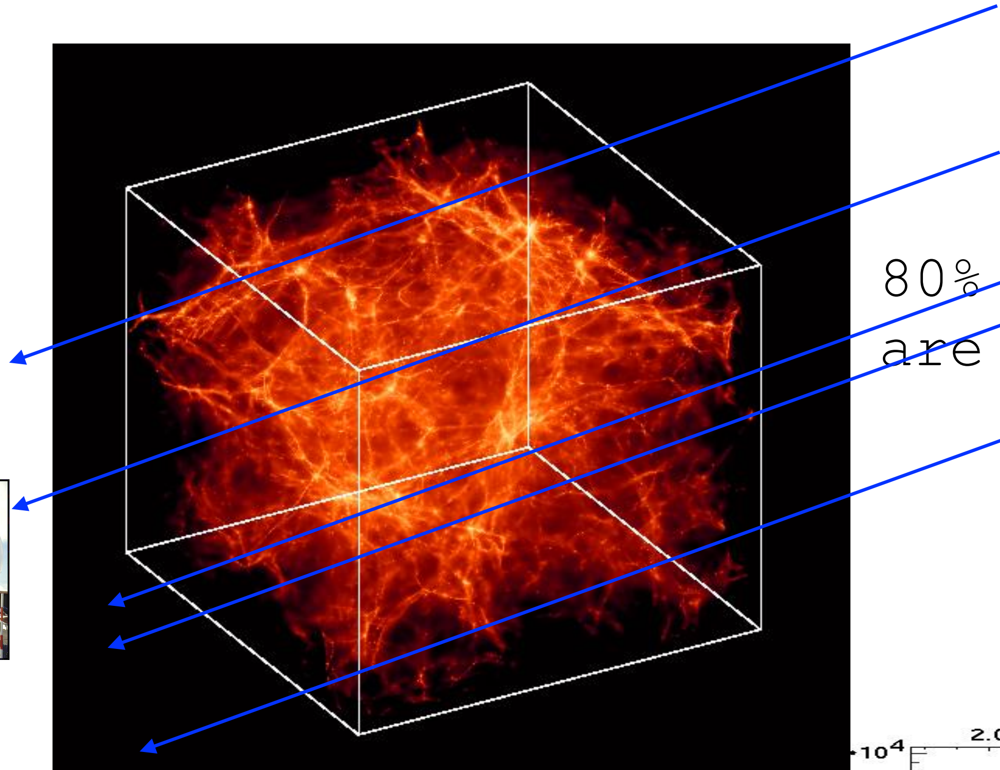
$\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_m(k)$

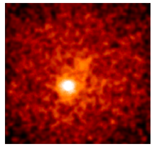
Cold dark matter prescription

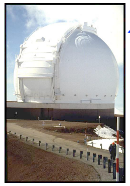
$\rho_m \rightarrow \rho_{cdm} \quad P_m(k) \rightarrow P_{cdm}(k)$



The Intergalactic Medium: Theory vs. Observations







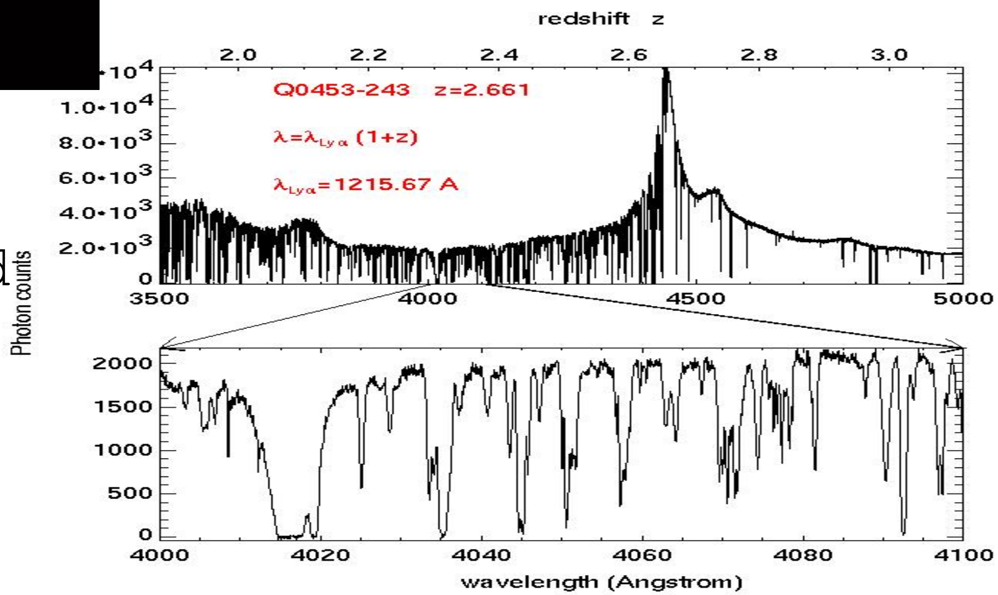
80% of the baryons at z=3 are in the **Lyman-α forest**

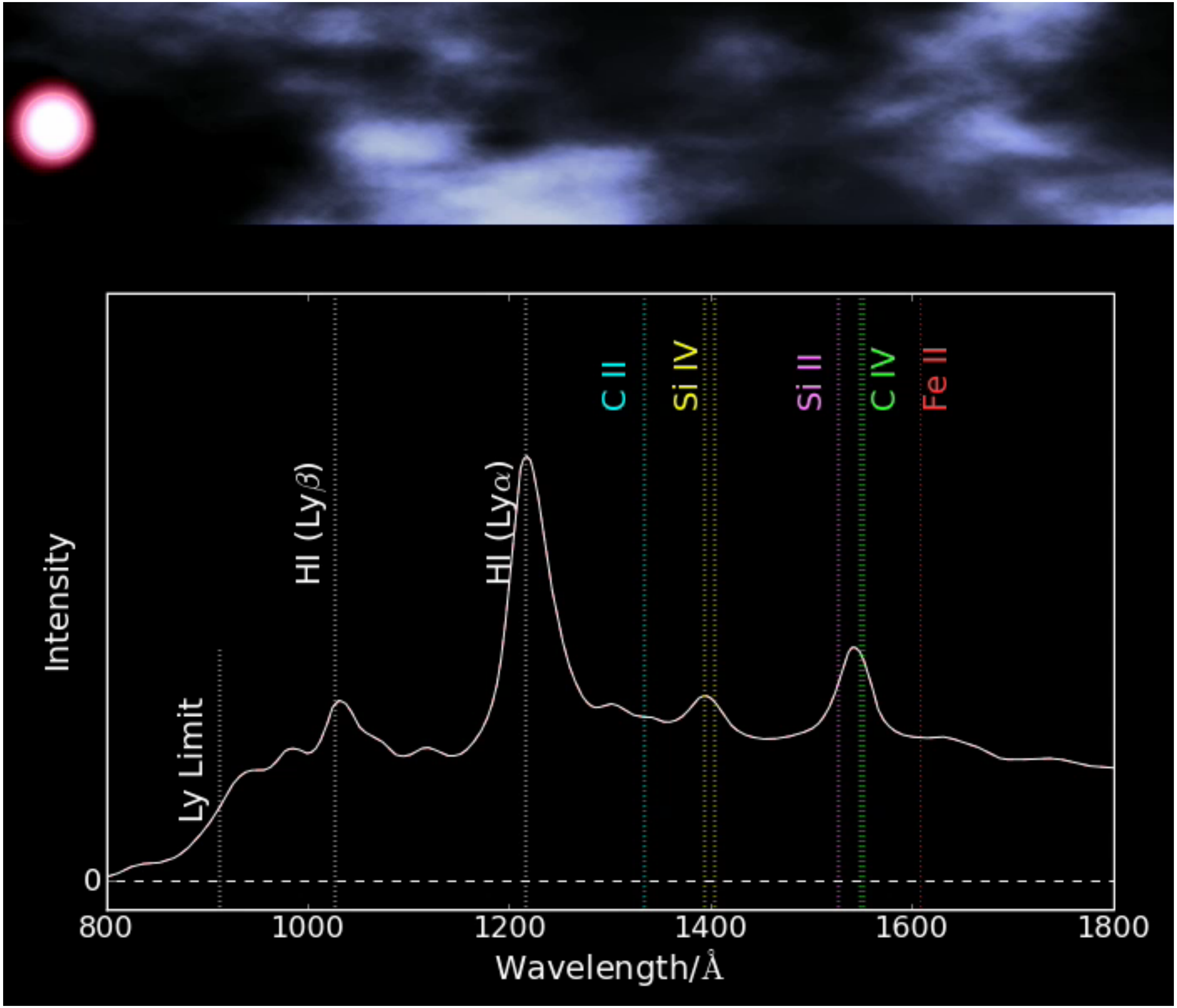
Bi & Davidsen (1997), Rauch (1998)
Review by Meiksin (2009)

baryons as tracer of the dark matter density field

$\delta_{IGM} \sim \delta_{DM}$

Croft+ 99,02
MV+ 04
McDonald+ 01,03

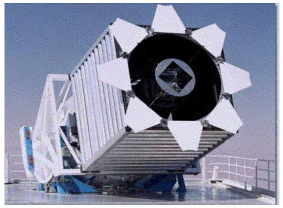




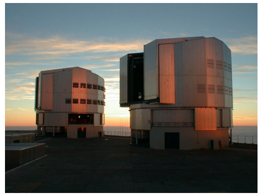
Intensity
Wavelength/Å
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II
0
800
1000
1200
1400
1600
1800

TOPIC	DATA	THEORY	RESULTS
BAOs	QSO Lya flux and coss correlation with QSOs 3D analysis – **low res**	Mocks	Clear detection, small tension with Planck
Cosmic neutrinos	IGM QSO Spectra **low res** 1D flux power	N-body/hydro sims	$\Sigma m_{\nu} < 0.12$ eV
Cold dark matter Coldness	IGM QSO Spectra **high res** 1D flux Power	N-body/hydro sims	$m_{WDM} > 3.3$ keV (thermal cross. sect.)

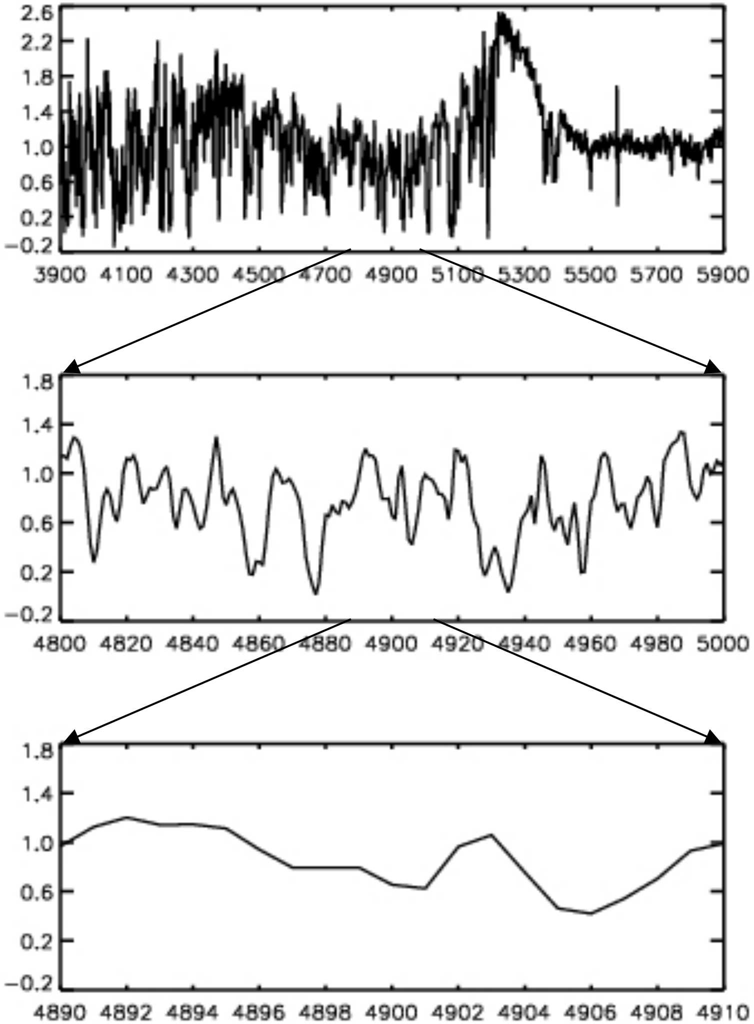
The data sets



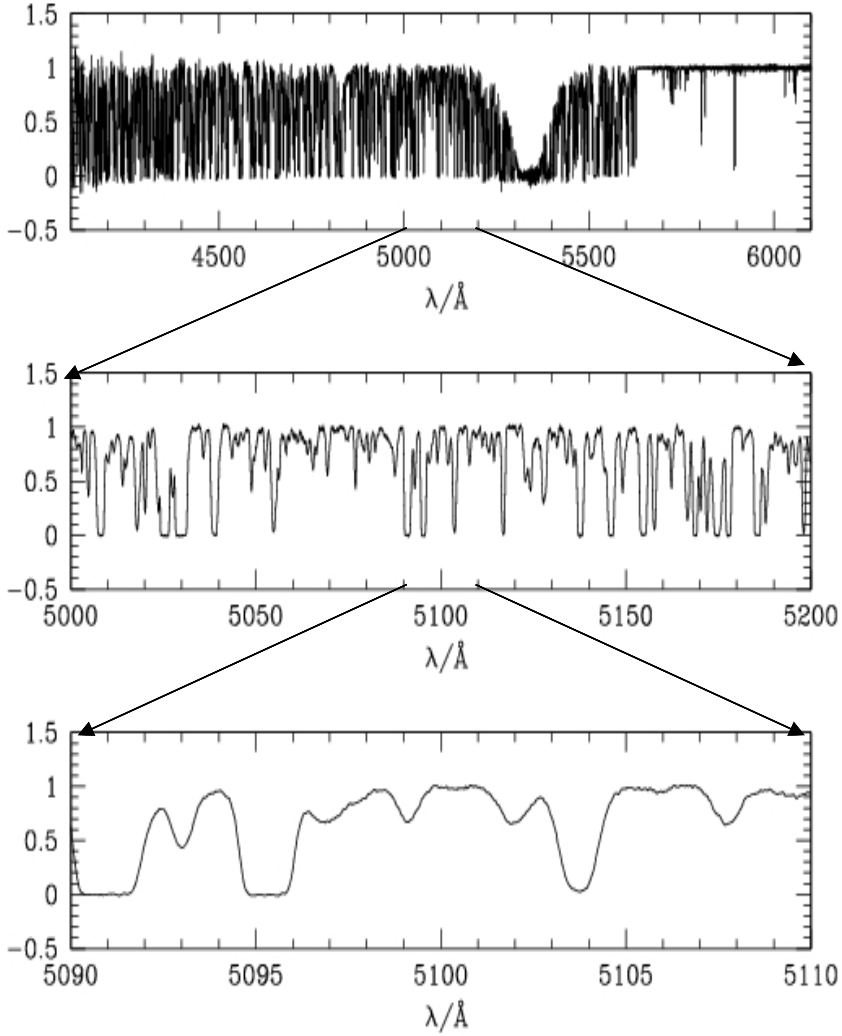
SDSS vs UVES



McDonald et al. 2005



Kim, MV+ 2004



SDSS
~10^4 LOW RESOLUTION LOW S/N

vs

UVES/KECK etc.
~10^2 HIGH RESOLUTION HIGH S/N

Key aspects

- High redshift (and small scales): possibly closer to linear behaviour

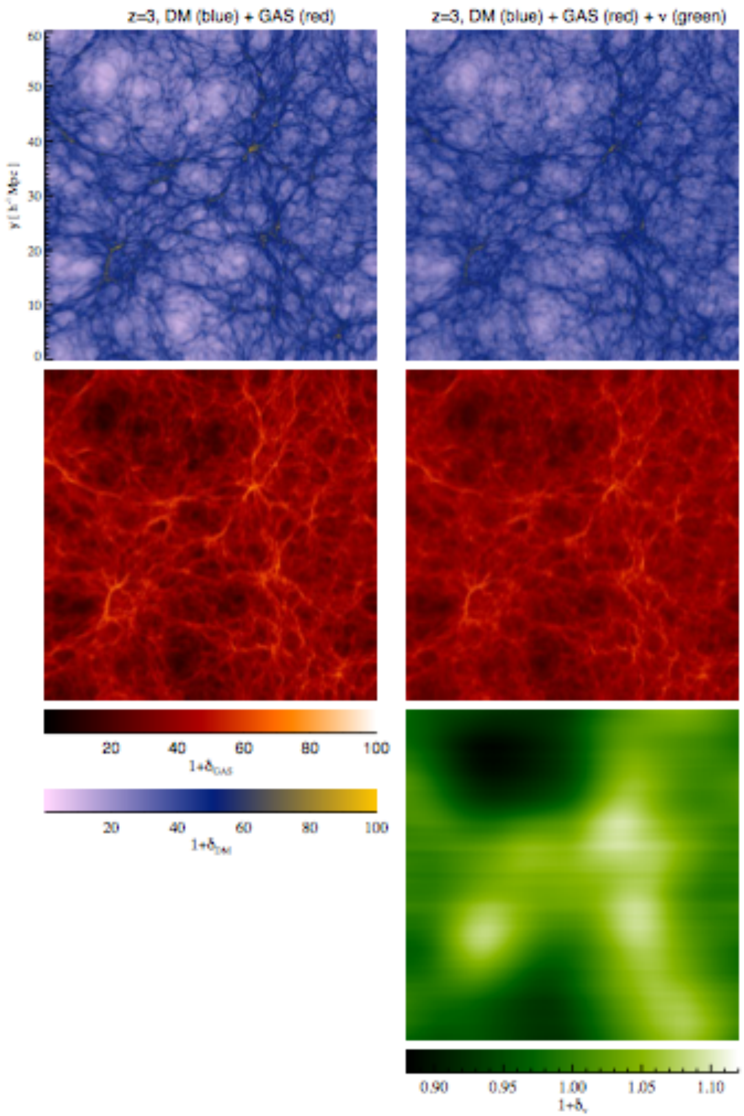
- 1D power: $$P_{1D}(k) = \frac{1}{2\pi} \int_k^{\infty} P_{3D}(x) x dx$$

- Matter probed at around the mean density

RESULTS FROM BOSS/SDSS-III

NEUTRINOS

NEUTRINOS IN THE IGM



N-body + hydro sims

Neutrino induced non-linear suppression understood and reproduced also with simple halo modelling (**Massara+ 15**)

Degeneracies with s8 are present

Neutrino induced effects on RSD (Marulli+11), BAOs (Peloso+15), mass functions and bias (Castorina+14) investigated

FROM IGM ONLY:

$$\Sigma m_{\nu} < 0.9 \text{ eV} (2\sigma)$$

Viel, Haehnelt, Springel 2010
Rossi+ 14, Villaescusa-Navarro+14

METHOD

DATA: thousands of low-res. Spectra for neutrino constraints. Few tens for cold dark matter coldness

SIMULATIONS: Gadget-III runs: 20 and 60 Mpc/h and (512^3,786^3,896^3)

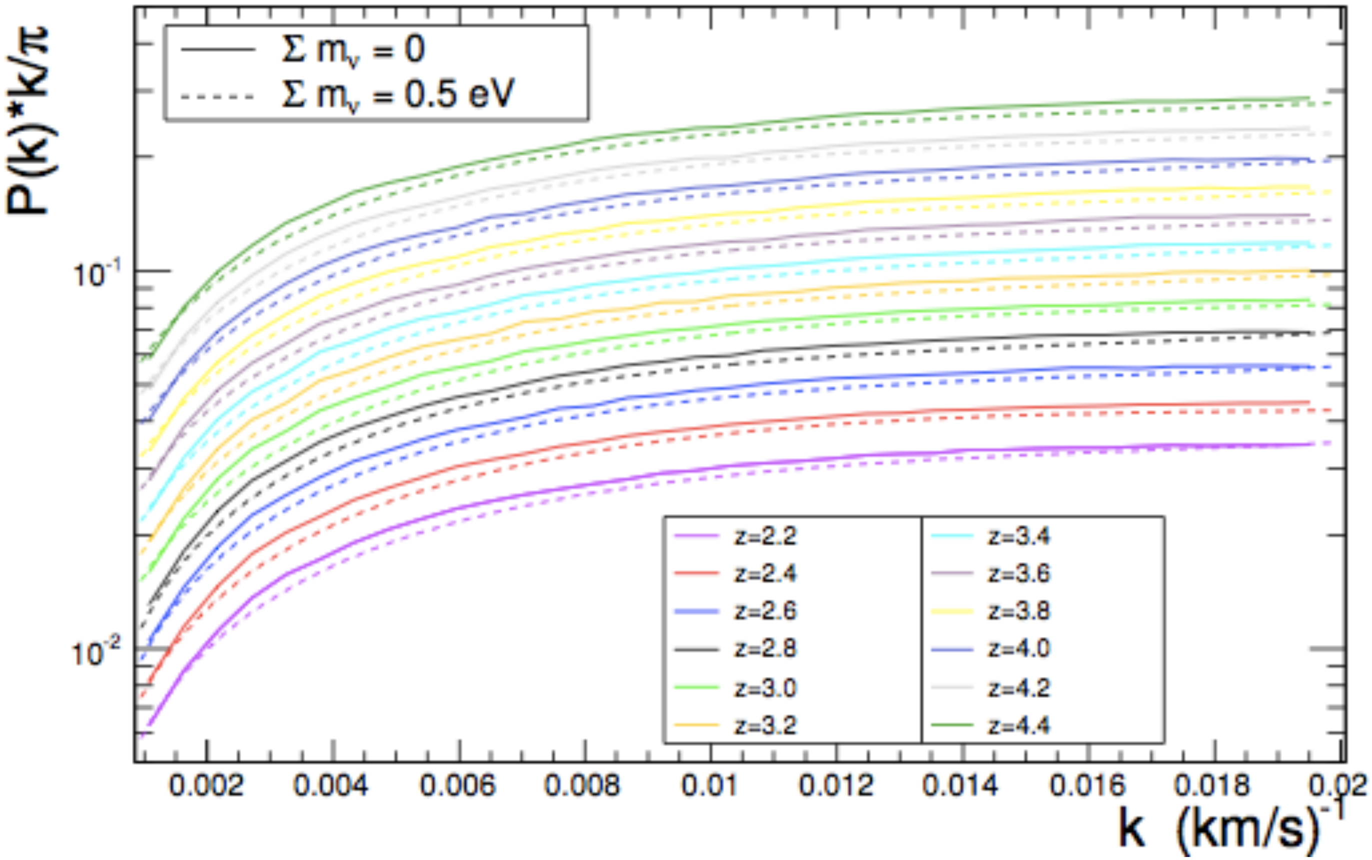
Cosmology parameters: σ_8, n_s, Ω_m, H_0, m_{WDM}, + neutrino mass
Astrophysical parameters: z_{reio}, UV fluctuations, T_0, γ, <F>
Nuisance: resolution, S/N, metals

METHOD: Monte Carlo Markov Chains likelihood estimator
+ **very conservative assumptions** for the continuum fitting and error bars on the data

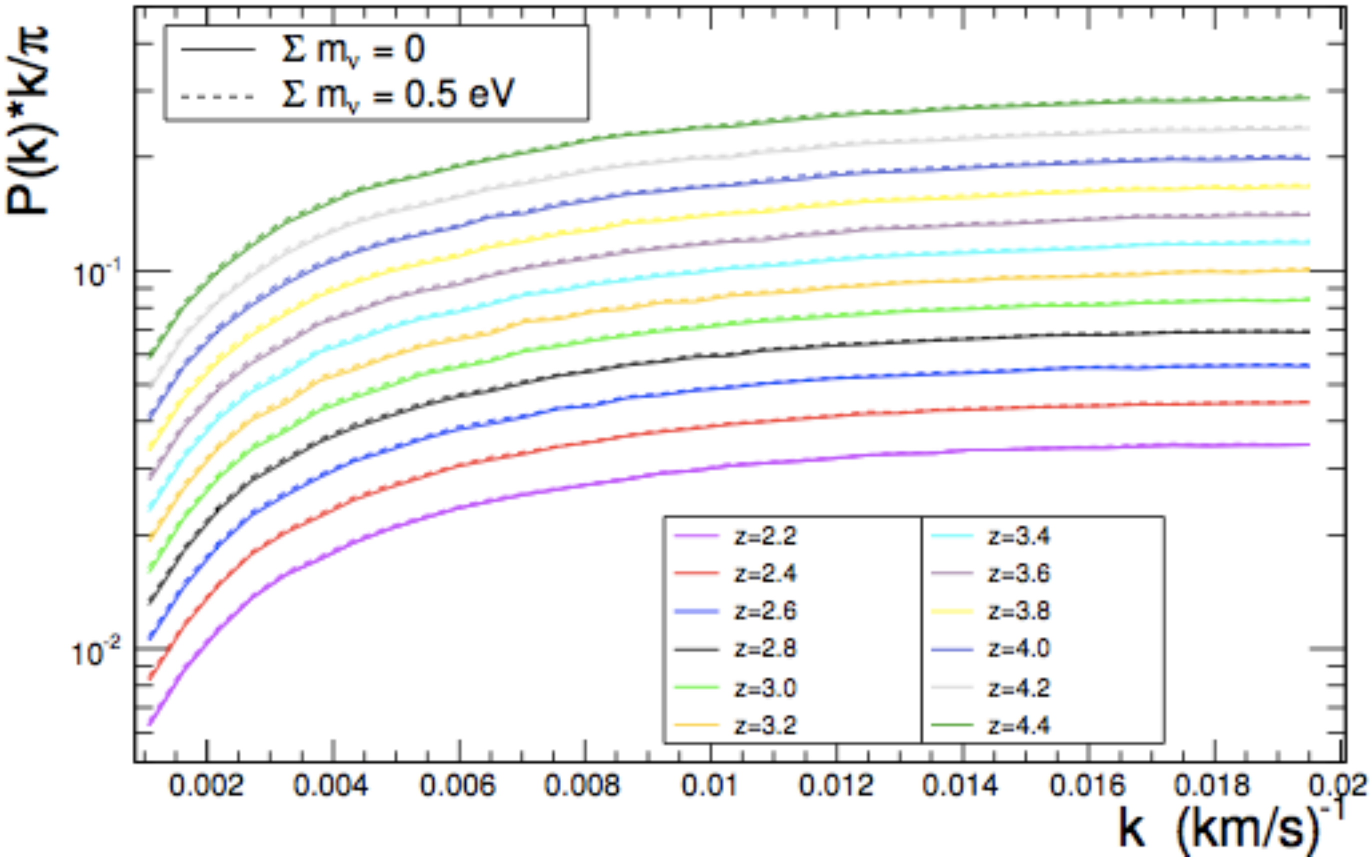
Parameter space: second order Taylor expansion of the flux power

$$P_F(k,z;\mathbf{p}) = P_F(k,z;\mathbf{p}^0) + \sum_i^N \frac{\partial P_F(k,z;p_i)}{\partial p_i}\Big|_{\mathbf{p}=\mathbf{p}^0} (p_i - p_i^0)$$ + second order

NEUTRINO IMPACT - I



NEUTRINO IMPACT - II

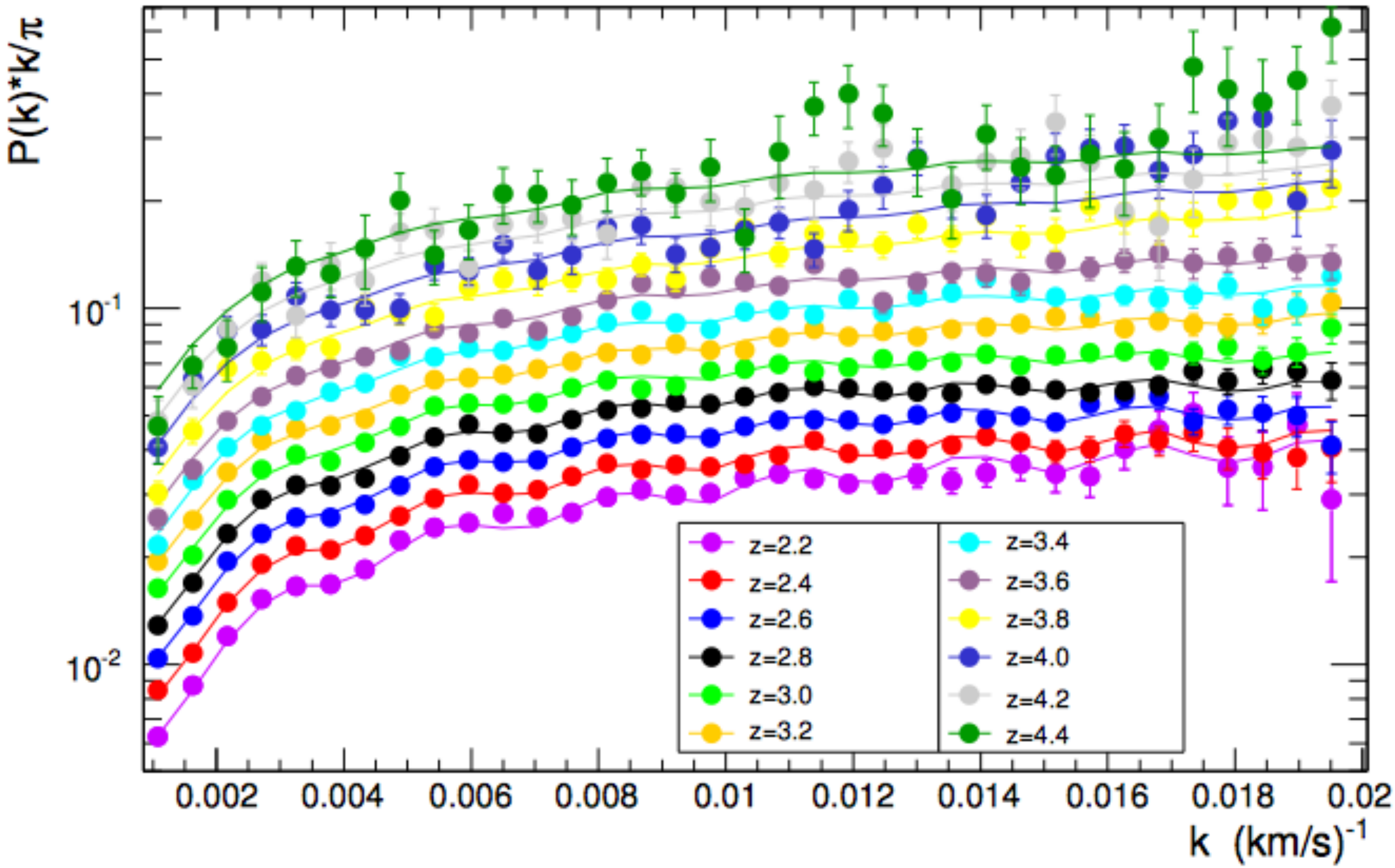


GROWTH OF STRUCTURES AT HIGH REDSHIFT

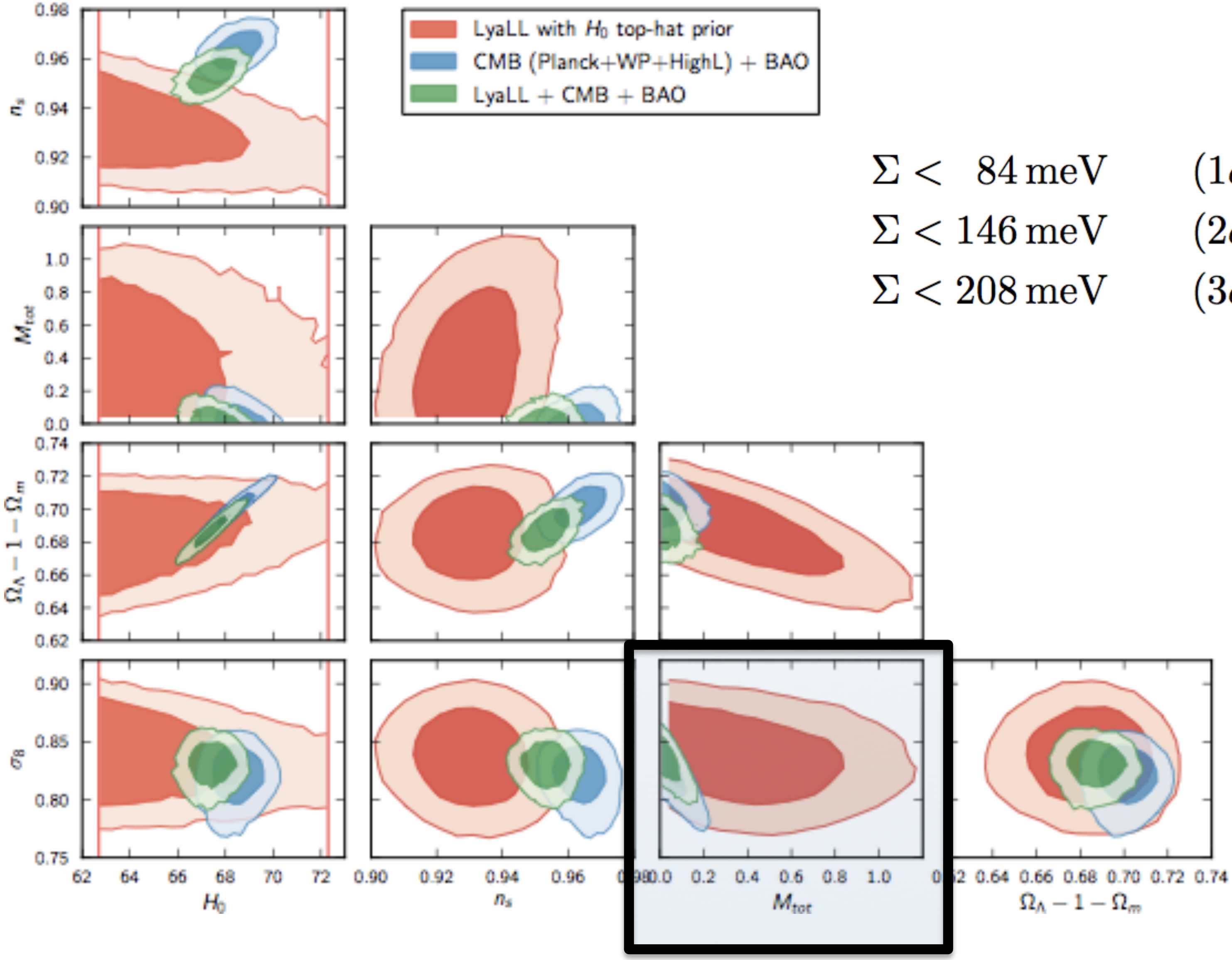
Constraint on neutrino masses from SDSS-III/BOSS Lyα forest and other cosmological probes

Nathalie Palanque-Delabrouille,[a,b] Christophe Yèche,[a] Julien Lesgourgues,[c,d,e] Graziano Rossi,[a,f] Arnaud Borde,[a] Matteo Viel,[g,h] Eric Aubourg,[i] David Kirkby,[j] Jean-Marc LeGoff,[a] James Rich,[a] Natalie Roe,[b] Nicholas P. Ross,[k] Donald P. Schneider,[l,m] David Weinberg[n]

1D Flux power spectrum evolution



BAYESIAN ANALYSIS



$$\Sigma < 84\,\mathrm{meV} \quad (1\sigma\,\mathrm{C.L.})$$
$$\Sigma < 146\,\mathrm{meV} \quad (2\sigma\,\mathrm{C.L.})$$
$$\Sigma < 208\,\mathrm{meV} \quad (3\sigma\,\mathrm{C.L.})$$

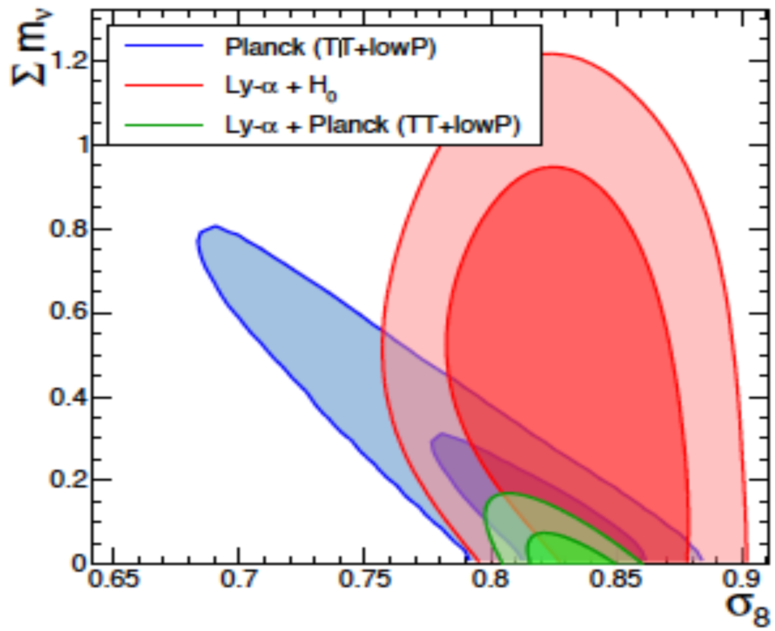
FINAL NUMBERS

Parameter	Lyα + H_0^{tophat} (62.5 ≤ H_0 < 72.5)	Lyα + CMB	Lyα + CMB + BAO	Lyα + CMB(A_L)
$10^9 A_s$	$3.2^{+0.5}_{-0.7}$	$2.20^{+0.05}_{-0.06}$	$2.20^{+0.05}_{-0.06}$	$2.18^{+0.05}_{-0.06}$
$10^2 \omega_b$	(fixed to 2.22)	2.20 ± 0.02	2.20 ± 0.02	2.22 ± 0.03
ω_{cdm}	$0.110^{+0.008}_{-0.013}$	$0.1200^{+0.0019}_{-0.0018}$	$0.1196^{+0.0015}_{-0.0014}$	0.1191 ± 0.002
τ_{reio}	(irrelevant)	$0.091^{+0.012}_{-0.013}$	$0.091^{+0.011}_{-0.013}$	$0.0871^{+0.012}_{-0.013}$
n_s	0.931 ± 0.012	0.953 ± 0.005	0.953 ± 0.005	$0.955^{+0.005}_{-0.006}$
H_0	< 70.9 (95%)	$67.2^{+0.8}_{-0.9}$	67.4 ± 0.7	$67.5^{+1.0}_{-1.1}$
$\sum m_\nu$ (eV)	< 0.98 (95%)	< 0.16 (95%)	< 0.14 (95%)	< 0.21 (95%)
A_L	(fixed to 1)	(fixed to 1)	(fixed to 1)	1.12 ± 0.10
σ_8	0.84 ± 0.03	$0.830^{+0.017}_{-0.013}$	$0.830^{+0.016}_{-0.012}$	$0.818^{+0.021}_{-0.014}$
Ω_m	$0.316^{+0.018}_{-0.021}$	0.316 ± 0.012	0.313 ± 0.009	0.312 ± 0.013

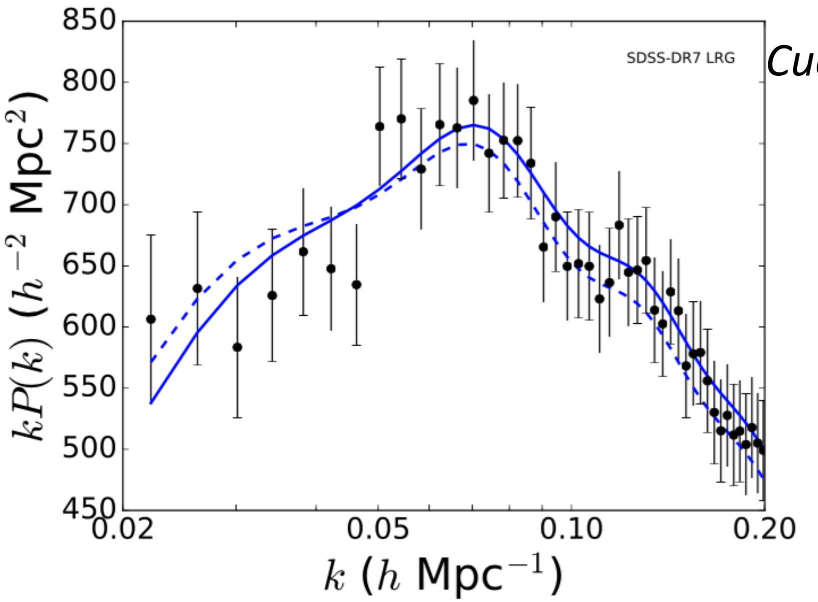
UPDATE using Planck 15

Palanque-Delabrouille+ 2015

Parameter	(1) Lyα + H_0^{Gaussian} ($H_0 = 67.3 \pm 1.0$)	(2) Lyα + Planck TT+lowP	(3) Lyα + Planck TT+lowP + BAO	(4) Lyα + Planck TT+TE+EE+lowP + BAO
σ_8	0.831 ± 0.031	0.833 ± 0.011	0.845 ± 0.010	0.842 ± 0.014
n_s	0.938 ± 0.010	0.960 ± 0.005	0.959 ± 0.004	0.960 ± 0.004
Ω_m	0.293 ± 0.014	0.302 ± 0.014	0.311 ± 0.014	0.311 ± 0.007
H_0 (km s^{-1} Mpc^{-1})	67.3 ± 1.0	68.1 ± 0.9	67.7 ± 1.1	67.7 ± 0.6
$\sum m_\nu$ (eV)	< 1.1 (95% CL)	< 0.12 (95% CL)	< 0.13 (95% CL)	< 0.12 (95% CL)
Reduced χ^2	0.99	1.04	1.05	1.05



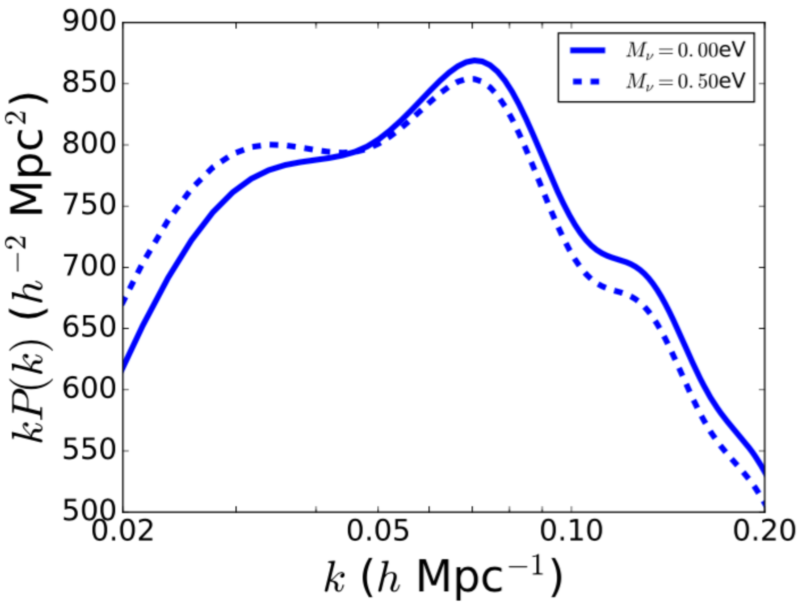
Constraints from galaxy clustering



Cuesta+16

• Galaxy clustering offers independent constraints that mainly exploit the shape

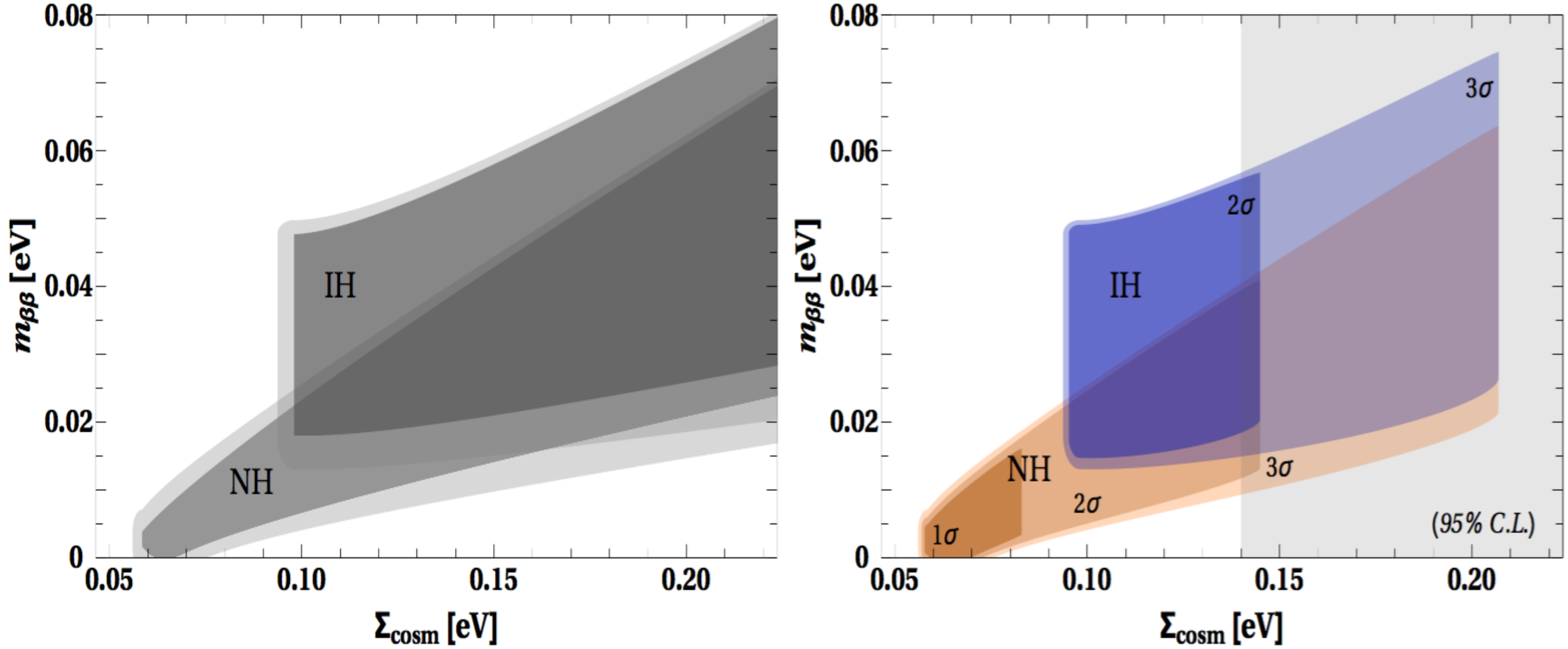
• Notice: galaxy bias Pgal=b^2 x Pmatter marginalized over but some assumptions on the bias b(k,z) model must be made



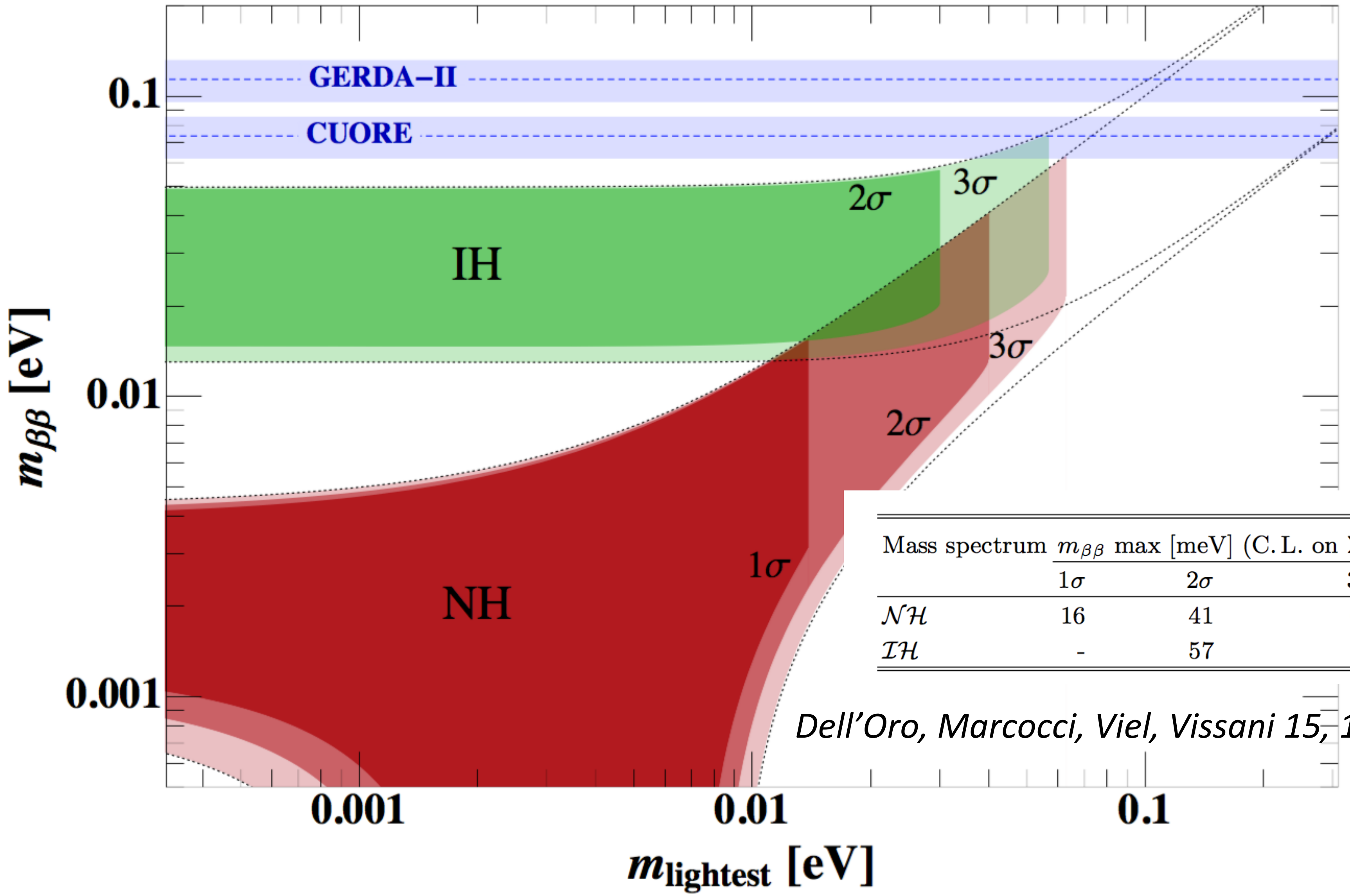
Parameter	CMB15+LRG+BAO
$100\ \omega_b$	$2.236^{+0.014}_{-0.014}$
$\omega_{\rm cdm}$	$0.1183^{+0.0012}_{-0.0011}$
n_s	$0.9677^{+0.0042}_{-0.0045}$
$\tau_{\rm reio}$	$0.083^{+0.016}_{-0.017}$
$ln(10^{10}A_s)$	$3.097^{+0.031}_{-0.034}$
H_0	$68.06^{+0.55}_{-0.55}$
σ_8	$0.831^{+0.016}_{-0.015}$
M_ν [eV]	< 0.13

Implications for neutrinoless double beta decay - I

Dell'Oro, Marcocci, Viel, Vissani 15,16



Implications for neutrinoless double beta decay - II

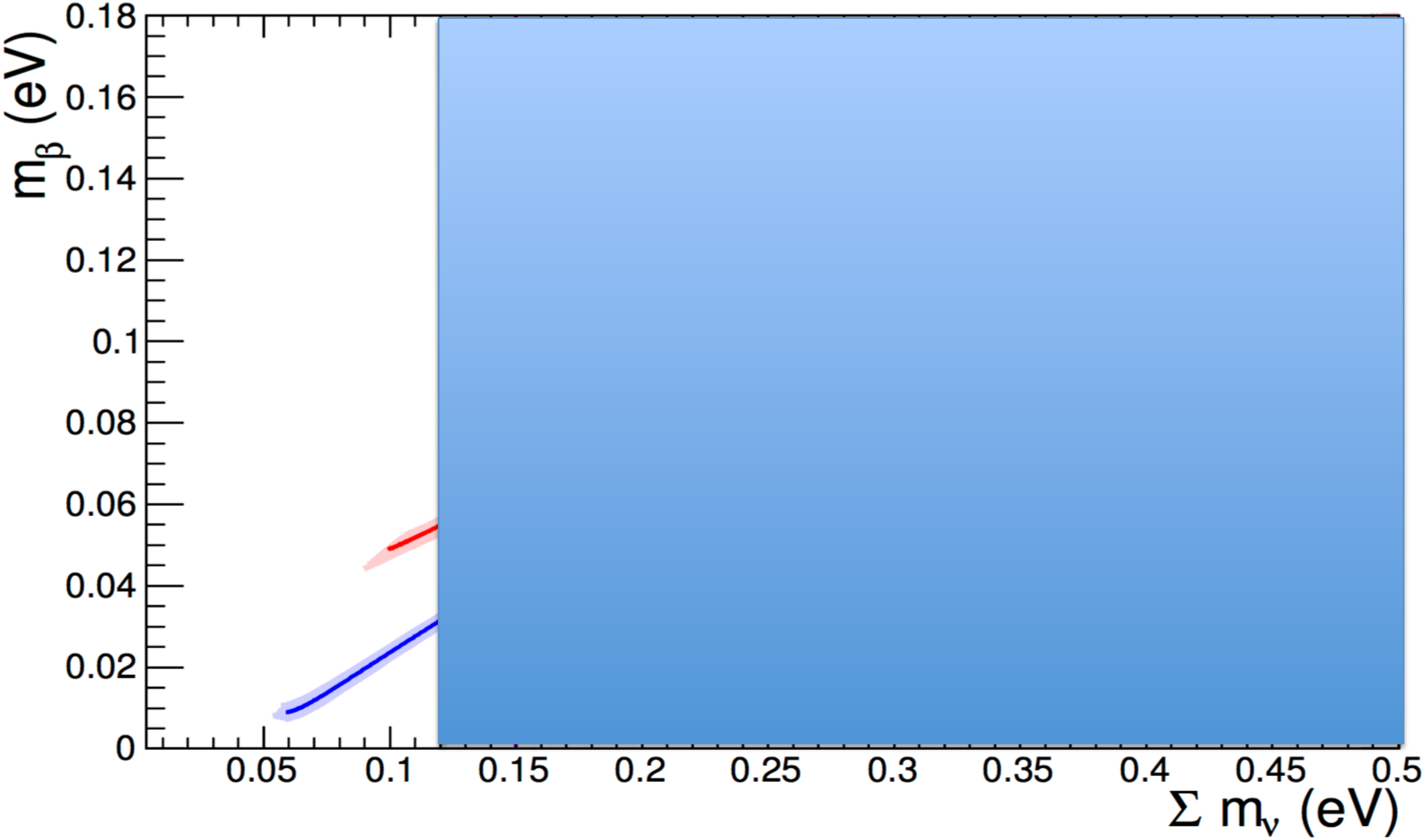


Mass spectrum	$m_{\beta\beta}$ max [meV] (C. L. on Σ)		
	1σ	2σ	3σ
$\mathcal{NH}$	16	41	64
$\mathcal{IH}$	-	57	75

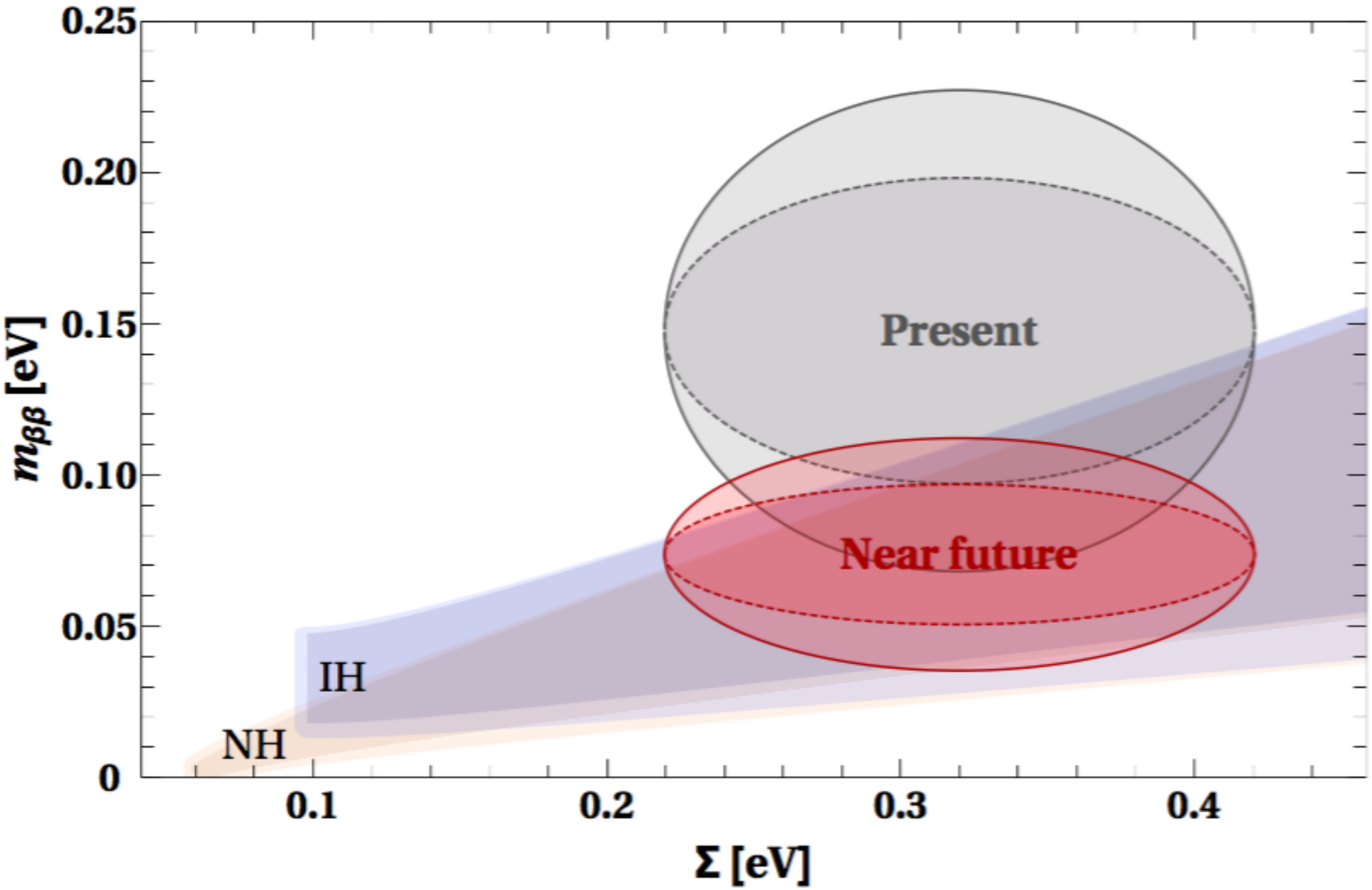
Dell'Oro, Marcocci, Viel, Vissani 15, 16

Implications for Tritium beta decay

$$m_\beta = \left(\sum_i |U_{ei}|^2 m_i^2\right)^{\frac{1}{2}} = \left(c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right)^{\frac{1}{2}}$$



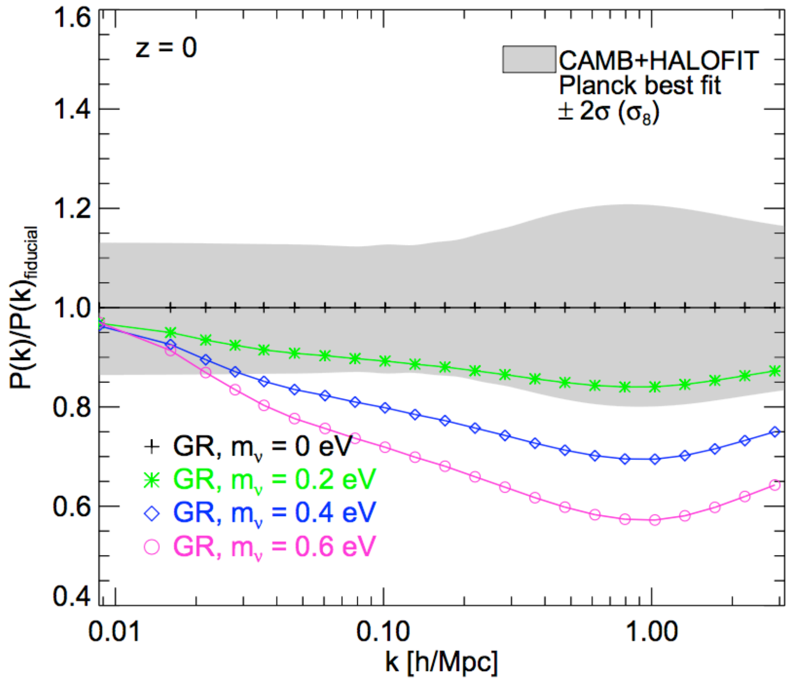
What if … non-zero neutrino claims are correct?



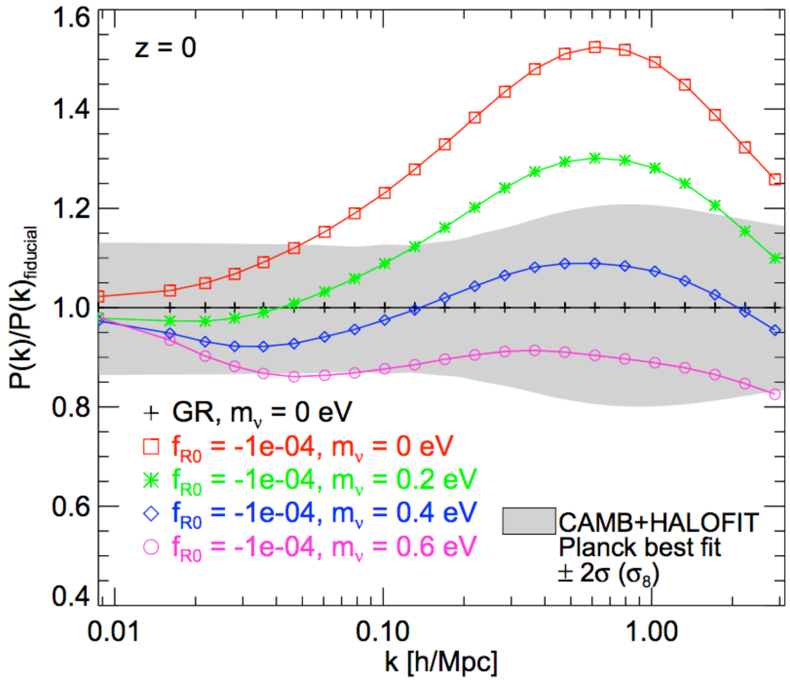
What if … large non-zero neutrino mass found?

Baldi, Villaescusa-Navarro, Viel, Puchwein, Springel, Moscardini, 2014

General Relativity + massive neutrinos



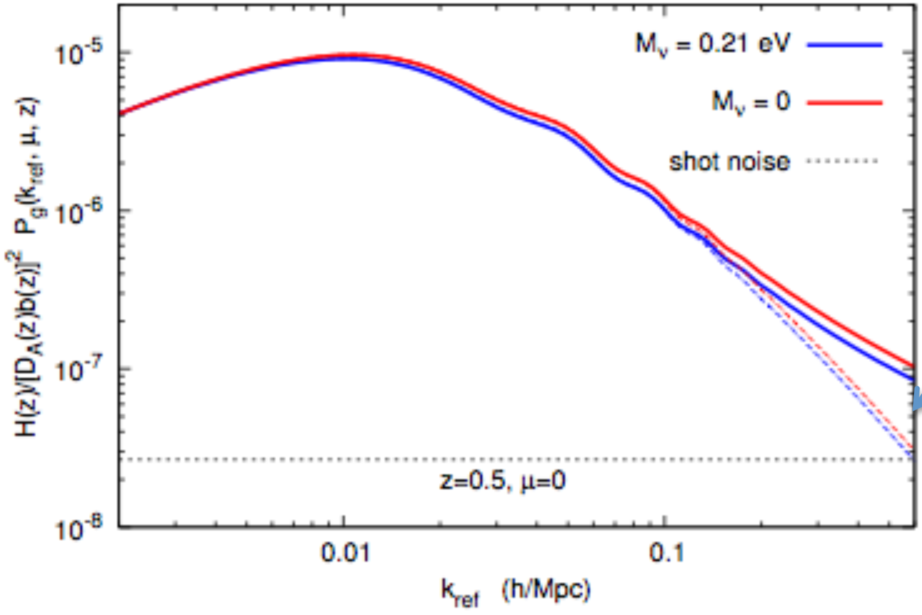
Modified gravity + massive neutrinos



FORECASTS

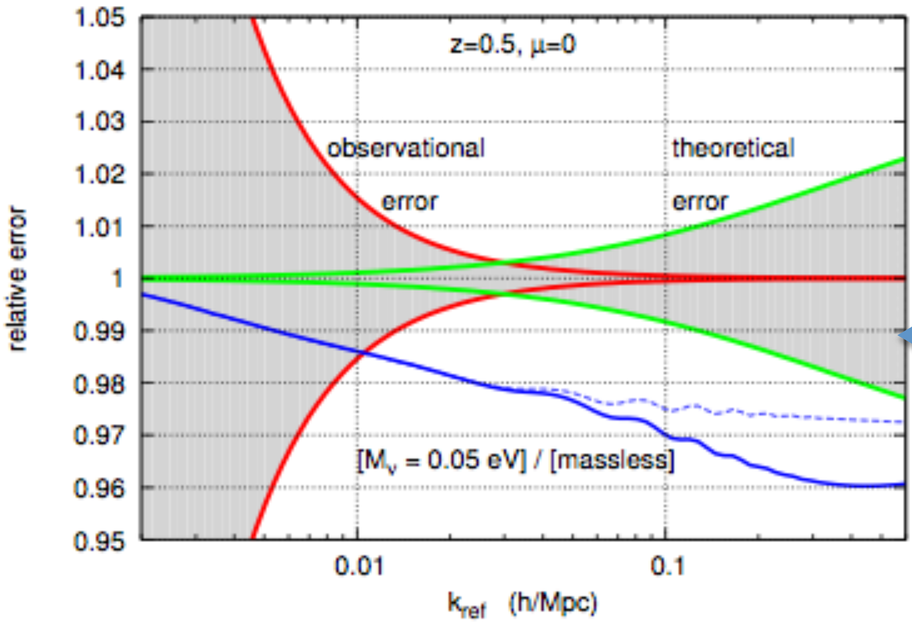
MASSIVE NEUTRINO FORECASTS for Euclid

Audren, Lesgourgues, Bird, Haehnelt, MV 2013



Non-linearities

- $\sigma(M_\nu)$=18 meV → 5 meV when going from 0.1 to 0.6 h/Mpc
- with conservative errors the improvement is modest
- with realistic error could be 20%



Need to be modelled accurately

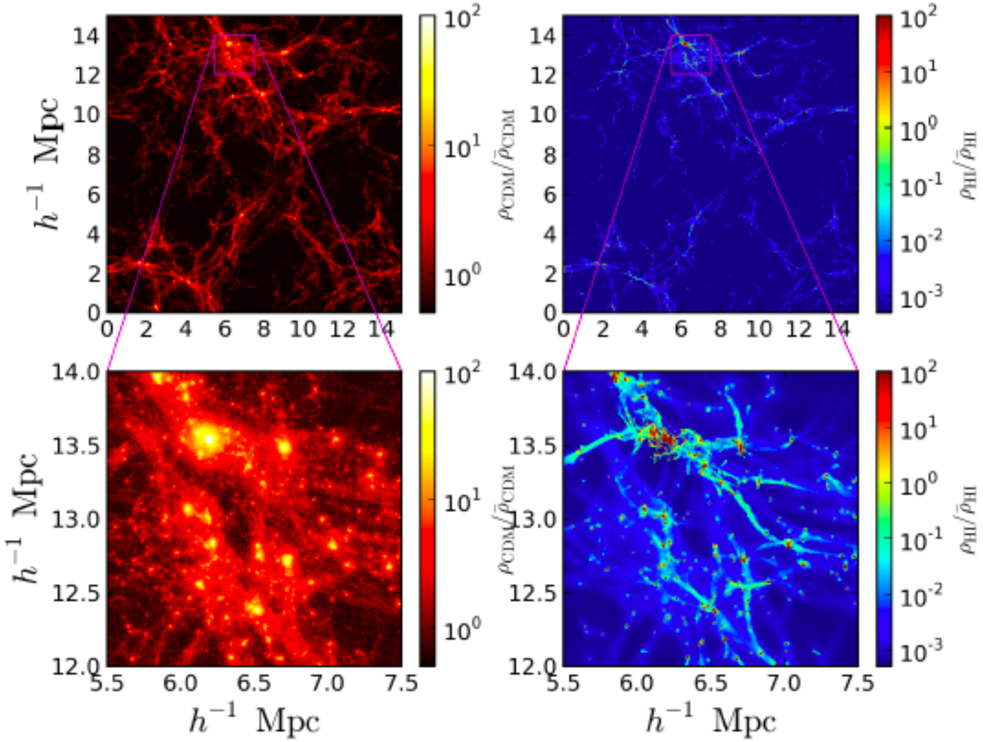
See also Costanzi et al. 2013 for clusters

$k_{\rm max}$ (h/Mpc)	un. err.	co. err.	$10^4\omega_b$	$10^4\omega_c$	$10^3 n_s$	$10^{11}A_s$	$10^3 h$	$z_{\rm reio}$	$3m_\nu = M_\nu$ (meV)
0.1	–	–	1.2	6.2	2.8	3.0	4.1	0.38	18
0.1	1/10	–	1.2	6.9	2.8	3.1	4.5	0.39	18
0.1	1/2	–	1.3	9.5	3.2	3.5	6.1	0.39	23
0.1	•	–	1.3	11	3.4	3.6	6.7	0.40	25
0.1	•	•	1.3	11	3.4	3.6	6.7	0.40	25
0.6	–	–	0.86	2.1	0.37	1.2	0.40	0.23	5.9
0.6	1/10	–	1.1	4.8	2.5	2.7	3.0	0.37	14
0.6	1/2	–	1.2	8.6	3.2	3.4	5.7	0.39	22
0.6	•	–	1.3	10	3.4	3.6	6.7	0.39	25
0.6	•	•	1.3	10	3.4	3.6	6.7	0.39	25

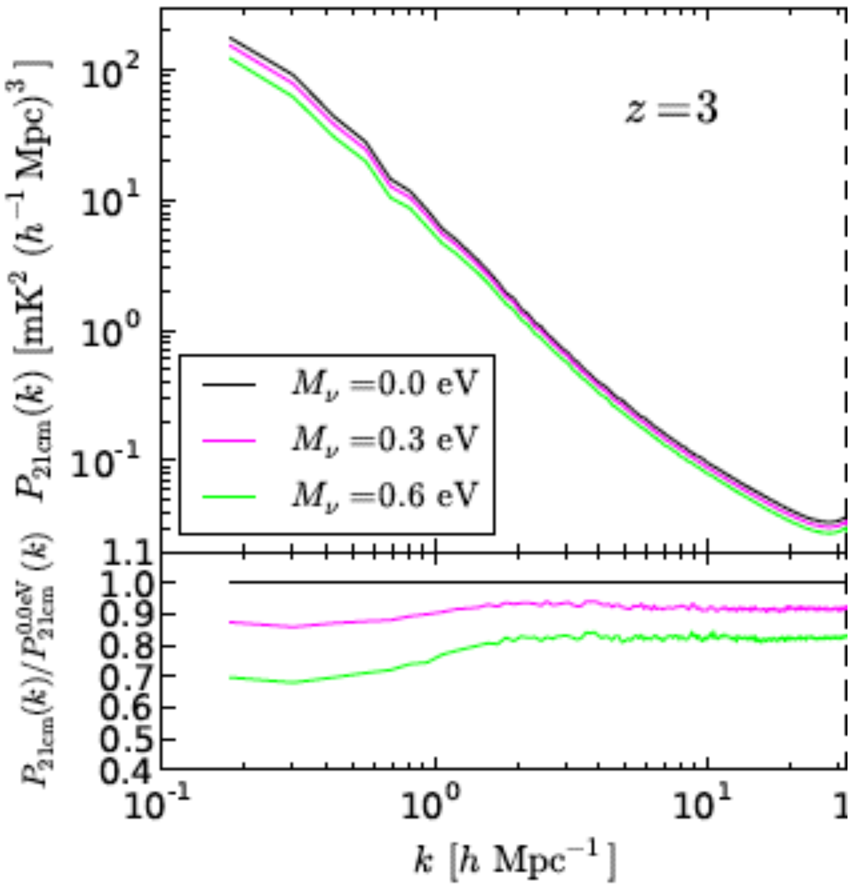
FROM ABSORPTION TO EMISSION - I

Villaescusa-Navarro, MV+ 2014

HI halo model	
Linear matter power spectrum	$P_m(k,z)$
Halo mass function	$n(M,z)$
Halo bias	$b(M,z)$
HI mass in halos	$M_{HI}(M,z)$
HI density profile in halos	$\rho_{HI}(r \mid M,z)$

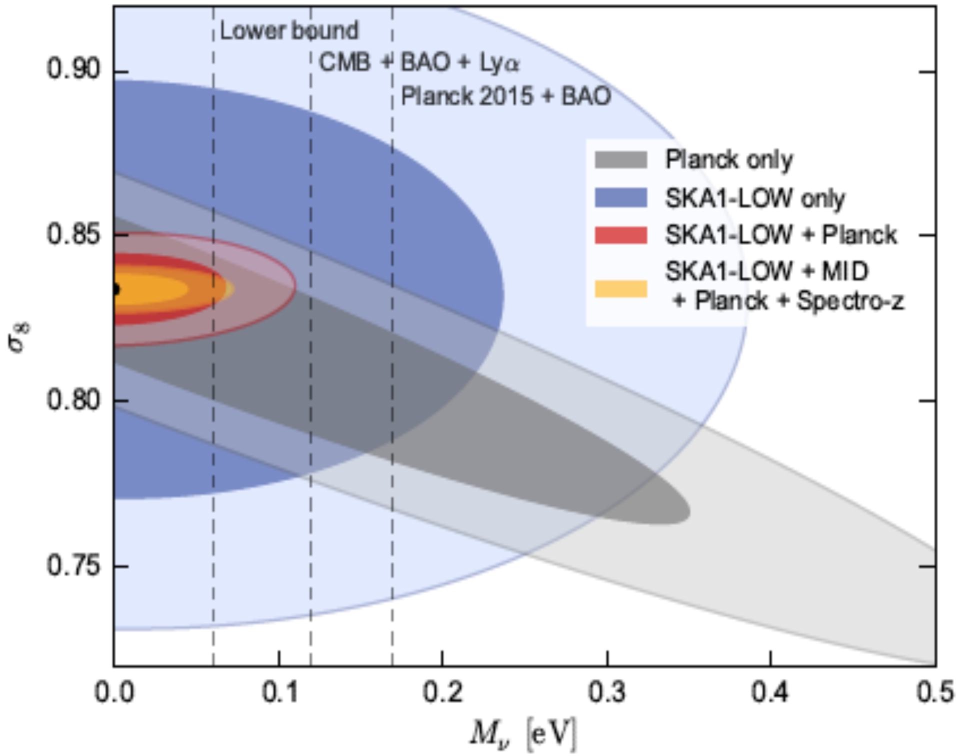


FROM ABSORPTION TO EMISSION:
NEUTRINOS in 21cm INTENSITY MAPPING with SKA



Villaescusa-Navarro, Bull, MV, arXiv: 1507.05102

$\sigma(M_\nu)$ = 0.06 eV (2σ error bar)



CONCLUSIONS

- From CMB data Δ N eff constrained to be < 0.2
- Limits on total neutrino mass 0.17-0.2 eV (2s C.L.)
- Adding Large Scale Structure data could provide hints for detection or tighten limits further depending on the data set used. Some recent WL and Cluster analysis are however in agreement with Planck
- Lyman-alpha forest data + CMB or galaxy clustering +CMB are the most constraining combination <0.12-13 eV
- Implications for neutrinoless double beta decay and Tritium beta decay are important
- Non-linear window on neutrino CNB is now open